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Review of Technologies for
Active Suppression for Fuel Tank Explosions
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Mary V. Bennett

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Booz•Allen & Hamilton Inc.
4141 Colonel Glenn Hwy, Suite 131
Dayton, OH 45431-1662

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13. ABSTRACT *(Maximum 200 Words)*

Several reactive suppression systems for fuel tank explosions were developed by the Navy and Air Force in the 1980s and showed potential in full-scale tests. Among these include the Linear Fire Extinguisher (LFE), Parker Hannifin Reactive Explosion Suppression System (PRESS), Scored-Canister System (SCS), and Nitrogen Inflated Ballistic Bladder (NIBB). Further development to bring these new technologies to maturity was discontinued mainly due to limitations in research funding and unresolved operational questions.

The purpose of this project was to assess the current status of previously developed reactive suppression systems for consideration as possible alternates to present aircraft fuel tank inerting systems, as well as locate state-of-the-art information on existing technologies.

Some common concerns exist among all the reactive suppression systems and should be addressed.

Of all the reactive systems investigated in this study, the LFE and the PRESS systems are the most viable. Investments into these technologies would not be futile. At the present time, substantial investment would be required to make the other reactive technologies viable solutions.

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TABLE OF CONTENTS

LIST OF FIGURES

Figure **Page**

1.0 Executive Summary

The goal of the Next Generation Fire Suppression Technology Program (NGP) is to develop and demonstrate, by 2005, retrofitable, economically feasible, environmentally-acceptable, and user-safe processes, techniques, and fluids that meet the operational requirements currently satisfied by Halon 1301 systems in aircraft, ships, land combat vehicles, and critical mission support facilities. The results will be specifically applicable to fielded weapon systems and will provide dual-use fire suppression technologies for preserving both life and operational assets.

The purpose of this project was to assess the current status of previously developed reactive suppression systems for consideration as possible alternates to present aircraft fuel tank inerting systems, as well as locate state-of-the-art information on existing technologies.

Several reactive suppression systems for fuel tank explosions were developed by the Navy and Air Force in the 1980s and showed potential in full-scale tests. Among these include the Linear Fire Extinguisher (LFE), Parker Hannifin Reactive Explosion Suppression System (PRESS), Scored-Canister System (SCS), and Nitrogen Inflated Ballistic Bladder (NIBB). Further development to bring these new technologies to maturity was discontinued mainly due to limitations in research funding and unresolved operational questions.

The first task of this effort assessed the fuel tank operating environment of several aircraft. This included a brief survey of the fuel tank operating environments (temperature, pressure, maximum allowable overpressure, design threat, fuel type, fuel tank configuration, etc.) of various aircraft to determine the operating conditions which must be satisfied by the existing technologies. Next, a literature search of previous efforts was performed that included a search of the Survivability/Vulnerability Information Analysis Center (SURVIAC) and Defense Technical Information Center (DTIC) databases, a review of recent Federal Aviation Administration (FAA) reports (generated as a result of the TWA-800 incident), a review of the Bureau of Mines information, and a review of information from the Gas Research Institute. A survey of U.S. Air Force, U.S. Navy, other Department of Defense (DoD) points of contact, and current manufacturers of these technologies assisted in the determination of their development status, if more advanced technologies have been developed, if any technological breakthroughs have occurred recently, and if these systems are recommended for specific types of aircraft (fighter/attack, bomber, cargo/transport). Information such as military service, date of development, technology developed, suppression mechanisms, ability to withstand the fuel tank operating environment, maintenance impact, logistics concerns, technological challenges, system initial and support costs, retrofit impact, requirements impact, suppressant/technology utilized, expulsion method, effectiveness, restart funding required, and testing performed assisted in the assessment of the potential viability of future investments in a particular alternative technology.

Some common concerns exist among all the reactive technologies and should be addressed. These include, but are not limited to, the following.

- Pyrotechnic/explosive devices in aircraft fuel tanks present a potential risk to the aircraft.
- Hydrodynamic ram could rupture the tank if the suppressant is discharged below the fuel level.
- Ultra-fast suppressant dispersion raises concerns about mounting bracket reaction loads.
- Possible tank overpressure could result from the discharge of agent sized for an empty tank when the tank is full.
- Inadvertent system operation may endanger maintenance personnel as well as result in high repair costs.
- Detection may be difficult since the detectors are line of sight.
- Introduction of water and the associated freezing point reducing agent into the fuel system may contaminate the fuel and may introduce corrosion.
- Installation and operation of the finalized system may be difficult depending upon the final design.

Of all the reactive systems investigated in this study, the LFE and the PRESS systems are the most viable. Investments into these technologies would not be futile.

At this time, the LFE is the most viable technology of the technologies investigated in this study. The LFE device has been tested with a myriad of halon alternatives. Numerous ballistic test series (0.50-cal API, 12.7-mm API, 23-mm HEI, and 30-mm HEI) have also been performed. However, more should be (and is being – summer of 2000) done to explore it. The upcoming test series will provide an opportunity to attempt to quantify the reaction load problem that has plagued this device.

The following advantages make the LFE a promising technology:

- Speed (response within 5 milliseconds),
- Suppressant speed – 1000 ft/sec,
- Efficient distribution, and
- Low weight (mostly suppressant).

More development is required to address the following LFE disadvantages:

- Power consumption,
- Detector technology lags,
- Ullage overpressure with halon, and
- Reaction forces from tube.

The PRESS system is also a viable technology. Funding and technical issues have limited its demonstration and the interest of Parker Hannifin to pursue this technology further (especially since they currently develop OBIGGS systems). However, their withdrawal does not mean that this system is "dead". Another manufacturer should "pick up the torch" and pursue this technology. The PRESS system is a patented system ("Explosion Suppression System", Bragg, K.R., Filed March 11, 1987, Patent Number 4,834,187). One potential avenue could include a patent licensing agreement with Parker Hannifin in the short term until the patent expires and the information becomes public domain.

The primary technical issue has been the nozzle design and its ease/cost of manufacture. It became evident that two types of nozzles are required for limiting overpressure (penetrating droplets—diesel type nozzle) and for preventing reignition (fog droplets—simplex type nozzle). Manufacturers (see Appendix D) of these types of nozzles should be contacted. Use of standard nozzles (such as conventional jet engine fuel nozzles) would provide cost savings since they are already manufactured items and are more than likely already flight-qualified.

The following advantages make the PRESS a promising technology:

- Fastest responding system – allows less suppressant, lighter weight,
- System designed for liquids like water – greater potential,
- Tank overpressure problem not evident, and
- Nozzles allow directed flow of suppressant.

More development is required to address the following PRESS disadvantages:

- Requires large scale proof-of-concept testing,
- More complex system – chance for malfunction despite high reliability components, and
- Possible expense in manufacture.

At the present time, substantial investment would be required to make the other reactive technologies viable solutions.

1.1 Task Objectives

The objective of this project was to assess the current status of previously developed alternative systems for consideration as possible alternates to present aircraft fuel tank inerting systems, as well as locate state-of-the-art information on existing technologies.

1.2 Technical Problems

Several reactive suppression systems for fuel tank explosions were developed by the Navy and Air Force in the 1980s and showed potential in full-scale tests. Further development to bring these new technologies to maturity was discontinued mainly due to limitations in research funding and unresolved operational questions. The problem addressed in this project was the determination of the status of these reactive suppression systems and to determine the viability of future investments into these technologies.

1.3 General Methodology

Reactive systems (such as the Linear Fire Extinguisher (LFE), Parker Hannifin Reactive Explosion Suppression System (PRESS), Scored-Canister System (SCS), and Nitrogen Inflated Ballistic Bladder (NIBB)) and active systems (Onboard Inert Gas Generator Systems (OBIGGS), Total Atmospheric Liquification of Oxygen and Nitrogen (TALON), carbon dioxide, exhaust gas, fuel fogging, anti-misting fuel, BlazeTech bubbler, air purging, fuel scrubbing, ullage washing, fuel tank ullage sweeping, catalytic combustor, and dry powders) were reanalyzed along with recently developed systems (utilization of gas generator technology, halon alternatives (HFC-125, FC-218, and CF_3I), etc.). This provided the background and understanding of these technologies to decide which ones require additional research and development.

The first task of this effort assessed the fuel tank operating environment of several aircraft. This included a brief survey of the fuel tank operating environments (temperature, pressure, maximum allowable overpressure, design threat, fuel type, fuel tank configuration, etc.) of various aircraft to determine the operating conditions which must be satisfied by the existing technologies. Next, a literature search of previous efforts was performed that included a search of the Survivability/Vulnerability Information Analysis Center (SURVIAC) and Defense Technical Information Center (DTIC) databases, a review of recent Federal Aviation Administration (FAA) reports (generated as a result of the TWA-800 incident), a review of the Bureau of Mines information, and a review of information from the Gas Research Institute. A survey of U.S. Air Force, U.S. Navy, other DoD points of contact, and current manufacturers of these technologies assisted in the determination of their development status, if more advanced technologies have been developed, if any technological breakthroughs have occurred recently, and if these systems are recommended for specific types of aircraft (fighter/attack, bomber, cargo/transport). Information such as military service, date of development, technology developed, suppression mechanisms, ability to withstand the fuel tank operating environment, maintenance impact, logistics concerns, technological challenges, system initial and support costs, retrofit impact, requirements impact, suppressant/technology utilized, expulsion method, effectiveness, restart funding required, and testing performed assisted in the assessment of the potential viability of future investments in a particular alternative technology.

1.4 Technical Results

The technical results of this effort include insight into the fuel tank operating conditions of selected fixed and rotary wing aircraft and the state-of-the-art of the reactive and active suppression systems investigated.

1.5 Important Findings and Conclusions

Of all the reactive systems investigated in this study, the LFE and the PRESS systems are the most viable. Investments into these technologies would not be futile.

At this time, the LFE is the most viable technology of the technologies investigated in this study.

At the present time, substantial investment would be required to make the other reactive technologies viable solutions.

1.6 Significant Hardware Developments

None.

1.7 Special Comments

None.

1.8 Implications for Further Research

Since the LFE and PRESS systems are the most viable technologies of the reactive suppression systems investigated, further research funding should be invested to bring these technologies to fruition.

2.0 Bibliography

Presented unclassified papers at:

- Halon Options Technical Working Conference, Albuquerque, New Mexico, May 2-4, 2000.
- Next Generation Fire Suppression Technology Program FY1999 Annual Research Meeting, Gaithersburg, Maryland, May 25-27, 1999.

3.0 Detailed Description of the Project

3.1 Assessment Of Operating Conditions

This section will describe the results of an assessment of existing fuel tank operating environments for both NGP-selected platforms (C-130, C-17, F/A-18, CH-47, and H-60) and other selected platforms. This included a brief survey of the fuel tank operating environments (temperature, pressure, maximum allowable overpressure, design threat, fuel type, fuel tank configuration, etc.) of various aircraft to determine the operating conditions which must be satisfied by any alternative technology.

3.1.1 Aircraft Types

Many different types of aircraft have evolved to accomplish an ever-increasing variety of military missions. Threats to each type of aircraft depend upon their required missions. Fuel system protection depends upon the damage modes associated with each type of threat. Representative military aircraft types and their missions are discussed briefly: [1]

- Interdiction aircraft (F-14, F-15, F-16, F/A-18, B-52, B-1B, B-2). These aircraft are expected to perform their missions with a high degree of survivability. The major threats for these types of aircraft are ground-to-air missiles and air-to-air missiles. Fighter/attack aircraft require fuel to be stored in both the wings and fuselage. In addition, some missions may require the use of external auxiliary fuel tanks. The fuel management process has to be considered in addition to the complexities of the location and types of fuel tanks that are installed in this type of aircraft. The larger bomber types usually store fuel in the wings, but there can be requirements for fuselage storage also.
- Close-air support attack (F-4, A-4, A-6, A-7, AV-8B, F-111, A-10). Close-air support aircraft will have fuel located in both the wings and the fuselage with provisions for external auxiliary fuel tanks and other stores. Because the preponderance of attacking munitions will be small arms or small caliber cannon sized, fire and explosion reduction techniques, which have proven effective against this type of threat, should be seriously considered. The A-10 aircraft, which was conceived as a fixed-wing close-air-support aircraft, was equipped with fire and explosion suppression material and devices.
- Troop support aircraft (C-5, C-130, KC-135, C-17). Sometimes these aircraft have been converted to "on-the-fly" delivery vehicles, or airborne troop carriers, and some have even been converted to heavily armed gunships. The conversion of aircraft like the C-130 to a combat role can be facilitated if the original design allows for add-on or alternative fuel system configurations. Access holes and tank construction should be compatible for both noncombat and combat rules.
- Helicopters. Helicopters fuel systems differ inherently from fixed-wing aircraft in that the fuel system can be smaller and simpler. Usually there are only a few fuel

tanks, and they are smaller in volume and presented area. Their locations are critical in that they must be close to the center of gravity of the aircraft, which is near the main rotor mast. For dual rotor aircraft fuel, the center of gravity is between the rotors.

3.1.2 Typical Aircraft Structural Limits

Most of the protection systems work by attempting to prevent the explosion from occurring or by reducing or mitigating the effects of the explosion if it occurs. Another method of reducing the ullage explosion hazard is by hardening the fuel tank structure so that it can withstand the overpressure that occurs. Modern aircraft fuel tank structures are capable of withstanding overpressures of 7 to 20 psi. Fuselage fuel tanks tend to be the weak link. For instance, 20 psi is the limit for the fuselage tanks of the F/A-18 and F-15. However, the F-15 wing foam suppression system is designed to hold overpressures of 45 psi maximum. Unsuppressed ullage explosions generally create overpressures of more than 100 psi, and structures capable of withstanding such pressures yet light and cheap enough to be practical do not yet exist. However, a number of mitigation techniques can reduce that to the 20 to 35 psi range. Thus, if it were possible to harden the structure to that range, a combined mitigation/hardening technique could work. [2]

3.1.3 Fuel Tank Operating Conditions By Platform

The following information is an excerpt from a more extensive effort. For that information, please reference SURVIAC-TR-99-007, Composite Affordability Initiative Phase II – Some Vulnerability Implications, April 1999 [4]. The platforms presented include the NGP platforms (C-130, C-17, F-16, F/A-18 C/D, CH-47, and H-60) and other platforms of interest (F-22, F-117, V-22, and Commanche).

3.1.3.1 NGP Platforms

C-130

Figure 1 identifies the C-130 fuel tank locations.

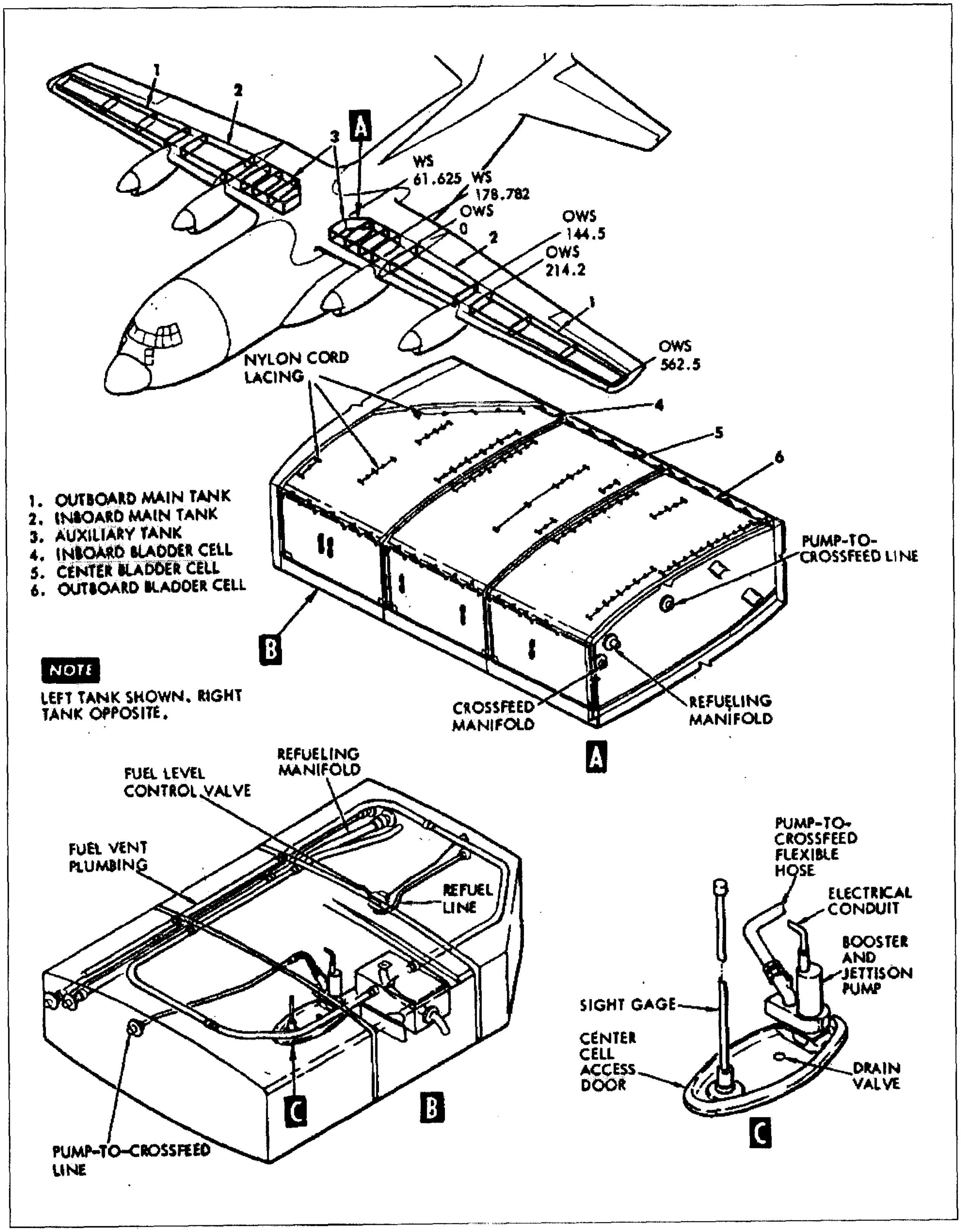


Figure 1. C-130 Fuel Tank Schematic

Table 1 summarizes the C-130 fuel tank capacities.

Table 1. C-130 Fuel Tank Capacity

	usable fuel level flight	
	gallon	LB
tank		
tank 1	1340	8710
tank 2	1230	7995
tank 3	1230	7995
tank 4	1340	8710
left auxiliary	910	5915
right auxiliary	910	5915
left external	1360	8840
right external	1360	8840
left fuselage	1796	11674
right fuselage	1796	11674
total internal	10552	68588
total	13272	86268

C-17

The C-17 fuel system consists of four independent fuel tanks, each supplying fuel to its associated engine.

The C-17 will be required to perform intertheater and intratheater delivery of combat forces, equipment, and supplies to austere airfields. The C-17 is planned to utilize multiple austere airfields, engine-running combat off-loads, airdrops, and a low altitude parachute extraction system (LAPES) depending on the mission. The C-17 will ingress/egress these airfields at low altitude terrain masking to evade detection and reduce exposure to hostile fire. [5]

The OBIGGS fuel tank inerting system (Figure 2) deters potential explosions by reducing the oxygen concentration in the fuel tank ullage below the level required to support combustion. The system removes oxygen from the fuel during refueling and provides a continuous supply of nitrogen enriched air, with four percent oxygen (NEA4), for inerting of the fuel tanks. This supply of NEA4 allows the fuel tank ullages to be inerted at the specified oxygen level to prevent fires and explosions. In addition, the OBIGGS will supply NEA to keep the fuel system inert for at least 48 hours on the ground with no power to the aircraft. Vulnerability reduction features of the C-17 fuel system (tanks one through four) are shown in Figure 3. The fuel tank design limit load pressure and ultimate pressure were not available for inclusion in this report.

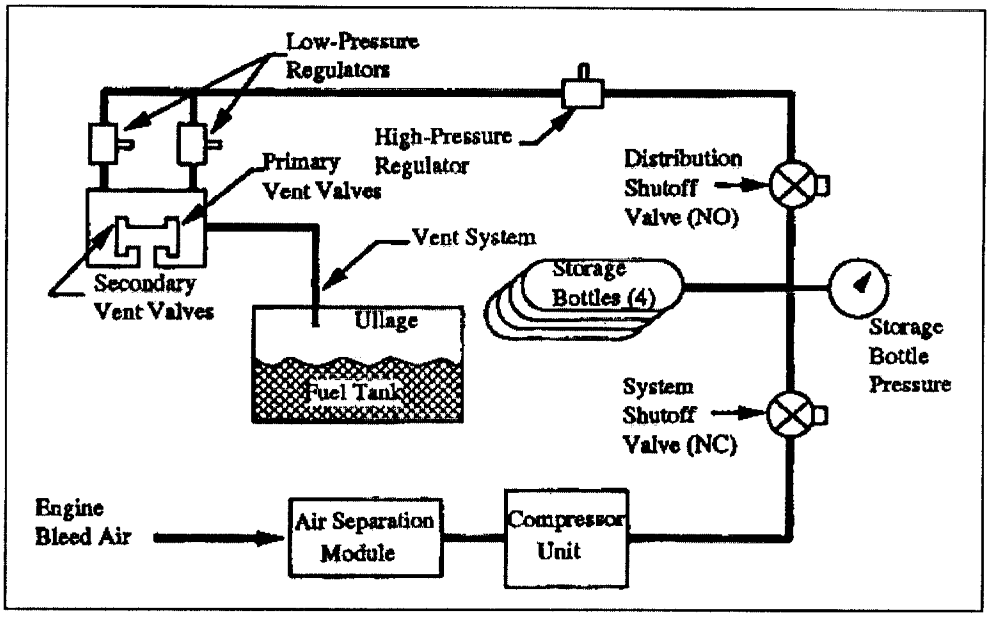


Figure 2. C-17 OBIGGS System

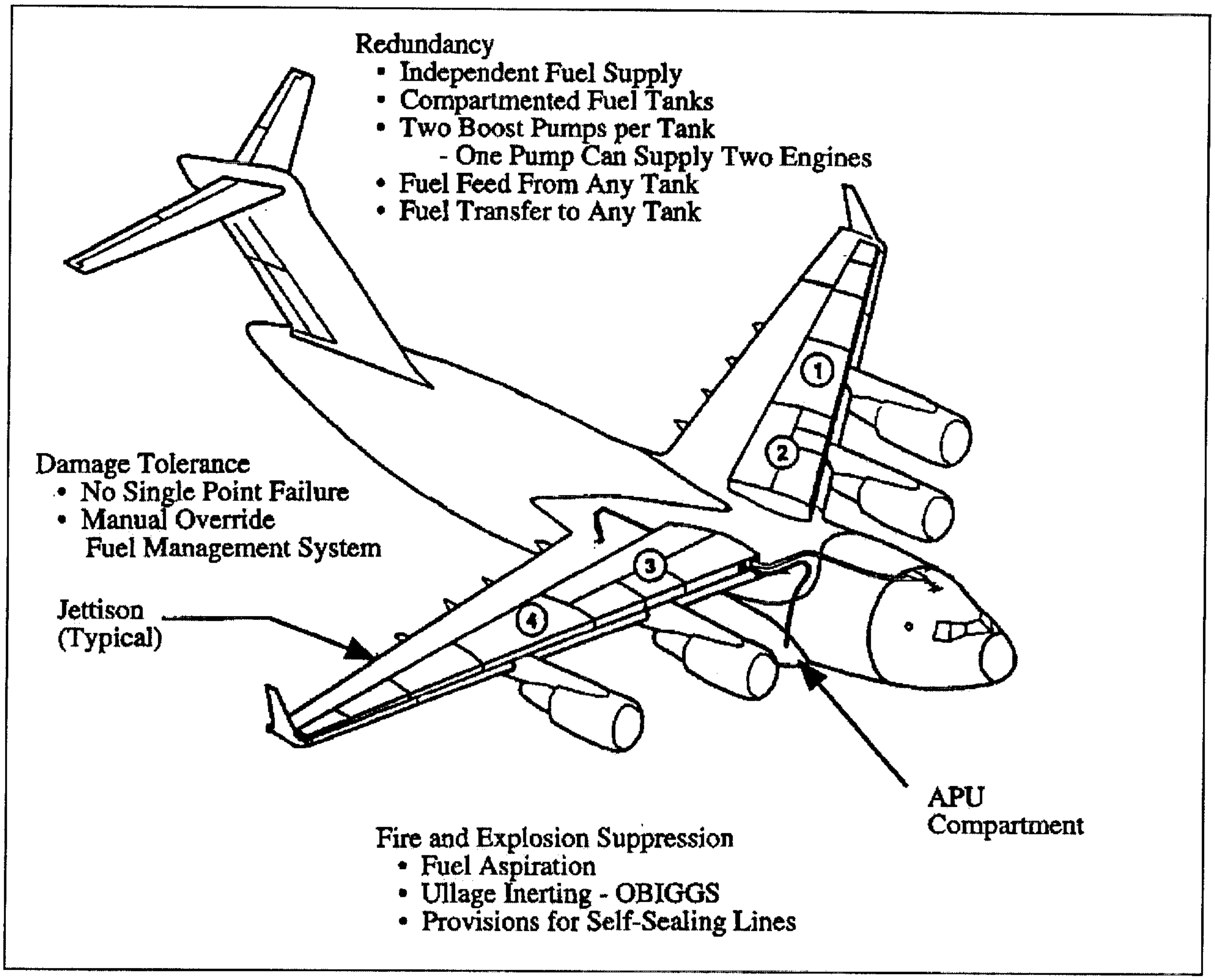


Figure 3. C-17 Vulnerability Reduction Features

Figure 4 shows a schematic of the C-17 fuel system. Each inboard tank is divided into four sections called the aft, forward, reservoir and feed compartments (Figure 5).

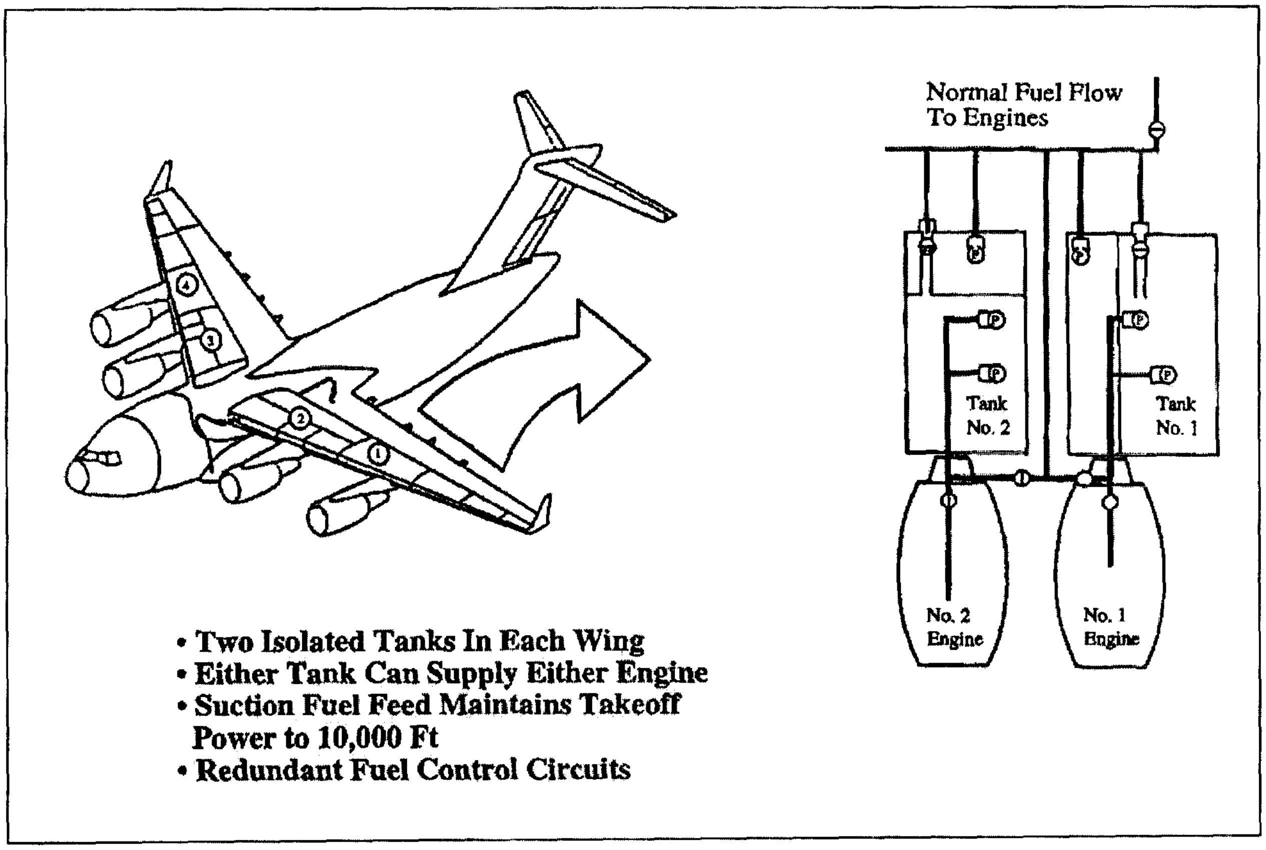


Figure 4. C-17 Fuel System Schematic

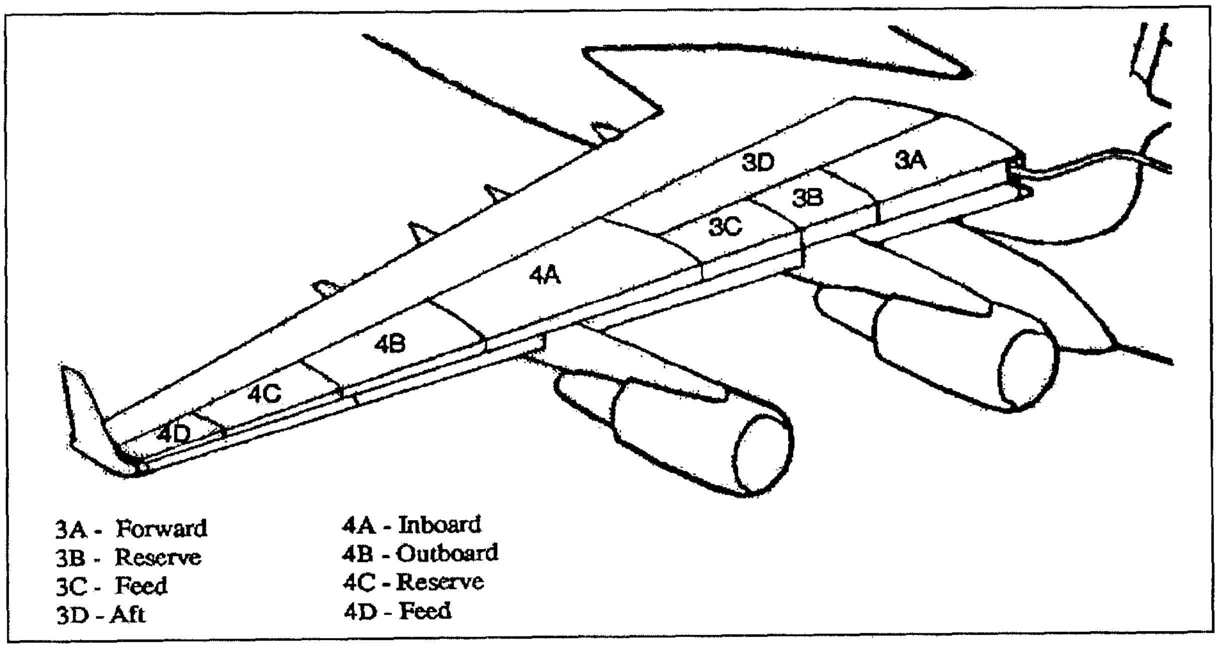


Figure 5. C-17 Inboard Tank Arrangement

Table 2 shows the tank capacities for the C-17 fuel system.

Table 2. C-17 Fuel Tank Capability

	Fuel Tank Capacities				
Fuel Tank	**Pounds**	**Kilograms**	**Gallons**	**Liters**	**% of Total Fuel**
Left Outboard (No. 1)	37798	17145	5608	21229	20.69
Left Inboard (No. 2)	53562	24295	7947	30083	29.31
Right Inboard (No. 3)	53562	24295	7947	30083	29.31
Right Outboard (No. 4)	37798	17145	5608	21229	20.69
Total Capacity	182720	82880	27110	102624	100.00

F-16

The design (critical) combat mission for the halon inerting system is the close air support mission that requires a number of excursions between 2,000 and 8,000 feet altitude. [6] This mission is representative of F-16 experience in Desert Storm and is the mission used to design and size the current halon inerting system. It is also the scenario used for previous vulnerability analyses and live fire tests for the F-16 weapon system. [7]

The Halon 1301 fuel tank inerting system of the F-16 was designed to provide protection against a .50 caliber armor piercing incendiary (API) bullet, but this was not a requirement dictated by USAF. It was approved by USAF, but established by General Dynamics. The .50 caliber API was selected through a joint effort of Operations Research and Analysis, Fuel Systems Design, and other groups within General Dynamics. [8]

Figure 6 identifies the tank locations.

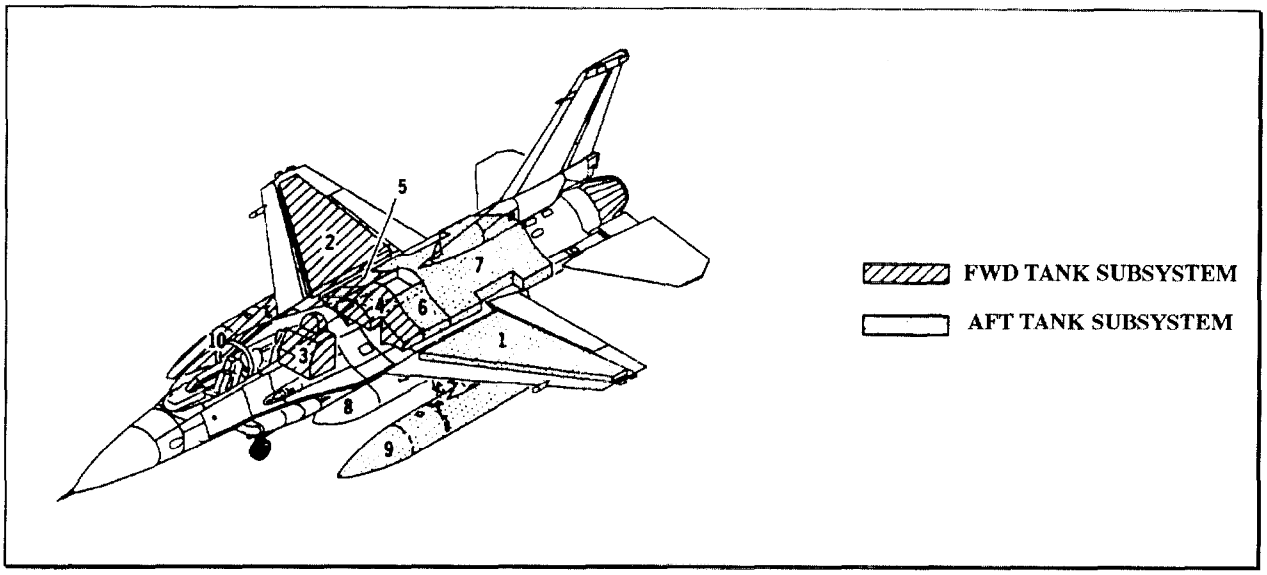


Figure 6. F-16 Fuel System Schematic

Table 3 presents the tank capacities as reported by the fuel quantity measuring system. The numbering of the tanks in this table corresponds to the tank locations shown in Figure 6.

Table 3. F-16 Usable Fuel Quantities

Fuel Tank and Location	Usable Fuel Quantity (LB) JP-5/8			
	F-16A	F-16B	F-16C	F-16D
1. Left Wing Internal	550 ± 100	550 ± 100	550 ± 100	550 ± 100
2. Right Wing Internal	550 ± 100	550 ± 100	550 ± 100	550 ± 100
3. F1 Fuselage 4. F2 Fuselage 5. Forward Reservoir	3250 ± 100	1890 ± 100	3250 ± 100	1890 ± 100
6. Aft Reservoir 7. A1 Fuselage	2940 ± 100	2940 ± 100	2810 ± 100	2810 ± 100
5. Forward Reservoir	480 ± 30	480 ± 30	480 ± 30	480 ± 30
6. Aft Reservoir	480 ± 30	480 ± 30	480 ± 30	480 ± 30
8. Centerline External	1890 ±100	1890 ±100	1890 ±100	1890 ±100
9. Left Wing External	2520 ±100	2520 ±100	2520 ±100	2520 ±100
10. Right Wing External	2520 ±100	2520 ±100	2520 ±100	2520 ±100
Total Internal Fuel	7290 ± 300	5930 ± 300	7160 ± 300	5800 ± 100
Total External Fuel	6930 ± 300	6930 ± 300	6930 ± 300	6930 ± 300

Note: Weights are based on JP-5/8 fuel at 6.8 pounds per gallon. Tolerances are due to indication errors because of variations in density resulting from temperatures, etc.

F/A-18

Figure 7 shows a schematic of the aircraft fuel tanks.

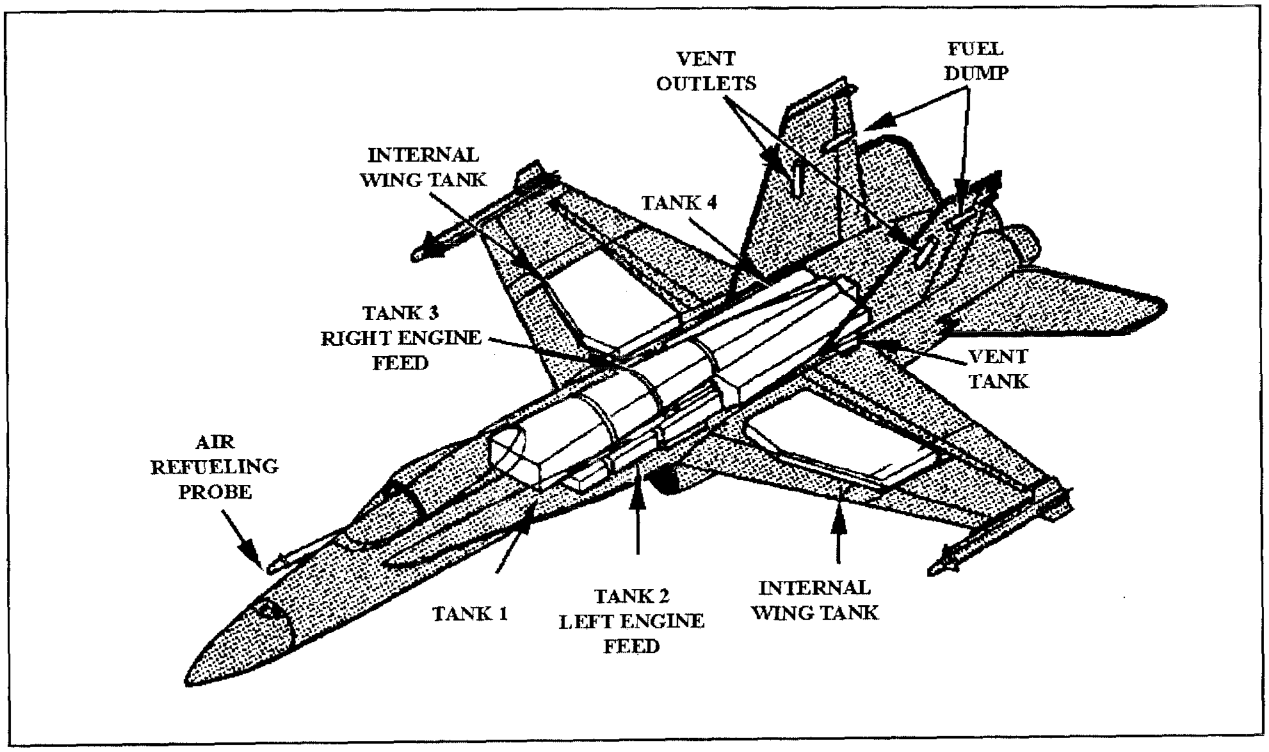


Figure 7. F/A-18A/B/C/D Fuel Tank Schematic

Table 4 shows the tank capacities for the F/A-18A/B/C/D fuel system.

Table 4. F/A-18A/B/C/D Fuel Tank Capacity

Tank	Gallons	Pounds JP-5	Pounds JP-4	% of Total Fuel - Elliptical	% of Internal Total - Cylindrical
Number 1	418	2840	2720	21.97	21.78
Number 2 - left engine Feed	263	1790	1710	13.82	13.71
Number 3 - right engine Feed	206	1400	1340	10.83	10.73
Number 4	532	3620	3460	27.96	27.72
Total fuselage	1419	9650	9230	74.57	73.94
Left internal wing	85	580	550	4.47	4.43
Right internal wing	85	580	550	4.47	4.43
Total internal	1589	10810	10330	83.50	82.80
External tanks					
Elliptical wing or Centerline tank	314	2140	2040	16.50	
Cylindrical wing or Centerline tank	330	2240	2150		17.20
Total w/elliptical External tank	1903	12950	12370	100.00	
Total w/cylindrical External tank	1919	13050	12480		100.00

CH-47

Table 5 shows the tank capacities for the CH-47 internal fuel system.

Table 5. CH-47 Fuel Tank Capacity

	Left Side (gallons)	Right Side (gallons)
Main tanks	278	274
Forward auxiliary tanks	122	119
Aft auxiliary tanks	118	117

H-60

The Blackhawk (H-60) helicopter has two 180 gallon fuel tanks.

3.1.3.2 Other Platforms

F-22

Figure 8 shows a schematic of the F-22 fuel system.

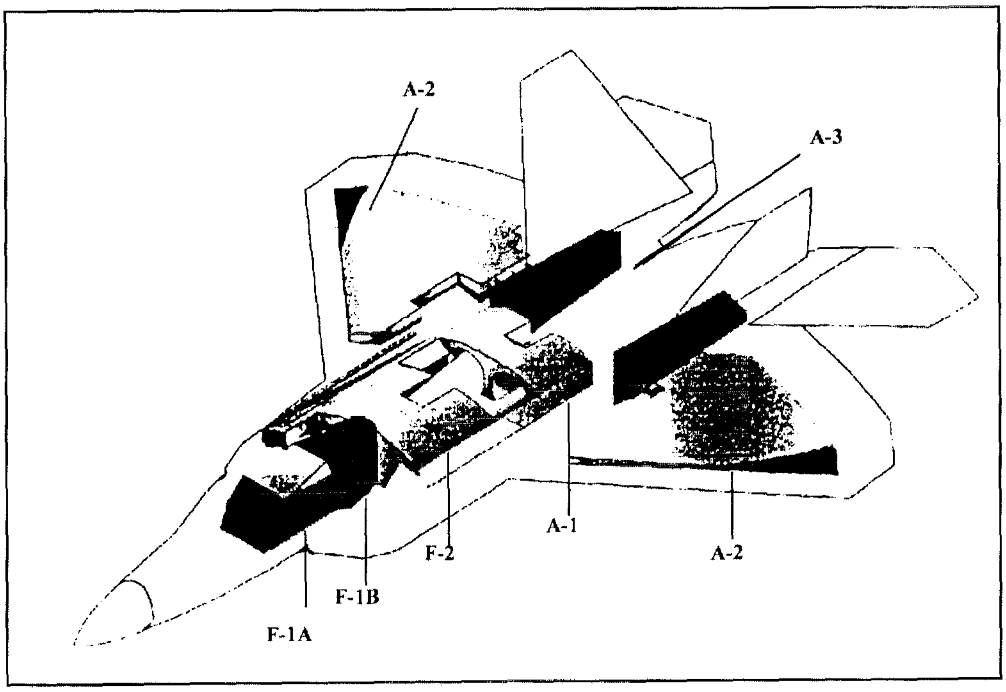


Figure 8. F-22 Fuel Tank Arrangement

The F-22 fuel tank capacities were not available at the time of this report.

F-117

Figure 9 shows a schematic of the F-117 fuel system.

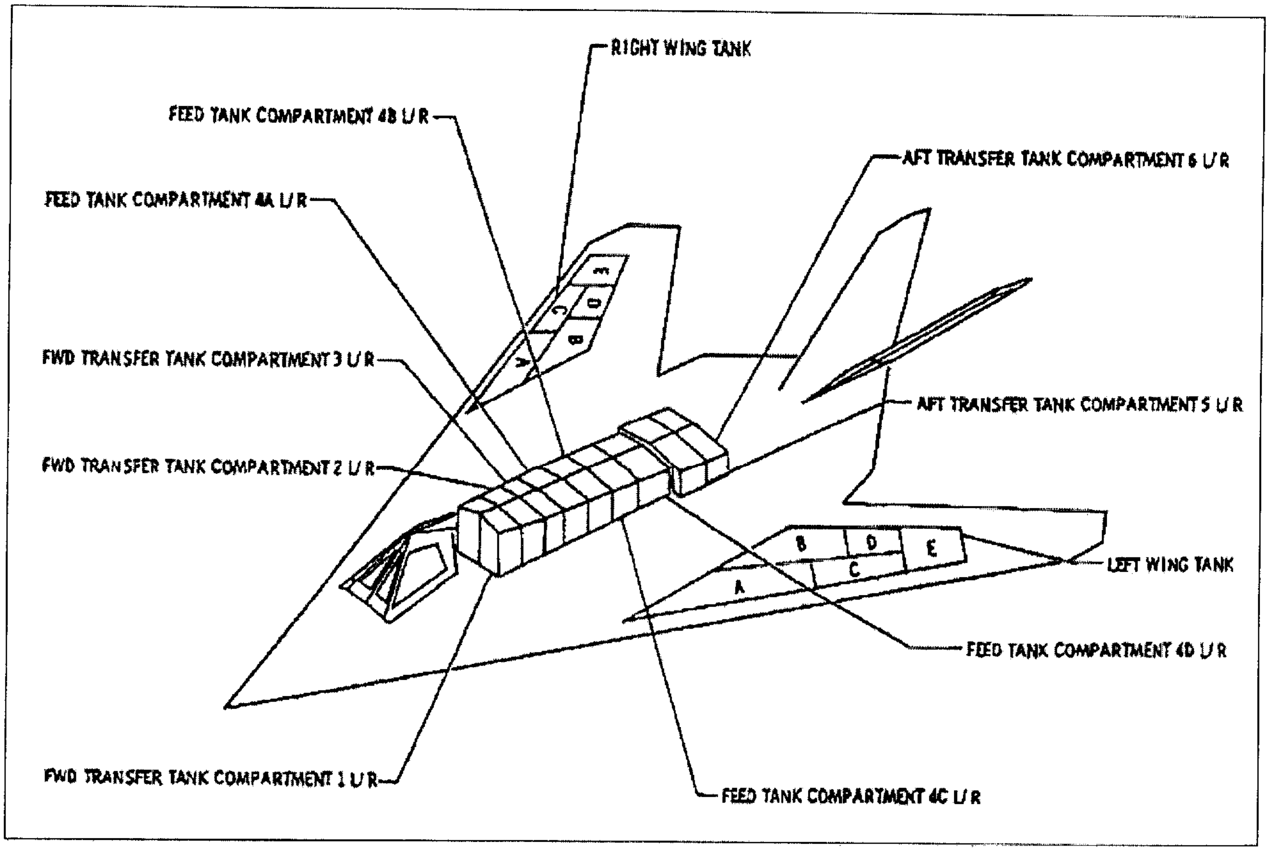


Figure 9. F-117 Fuel System Schematic

Table 6 shows the tank capacities for the F-117 fuel system.

Table 6. F-117 Fuel Tank Capacities

Tank	Maximum Usable Fuel	JP-4	JP-8	
	Gallons	Pounds	Pounds	% of Total Fuel
Forward transfer L	415.4	2700	2800	14.8357
Forward transfer R	415.4	2700	2800	14.8357
Feed L	369.2	2400	2500	13.1857
Feed R	369.2	2400	2500	13.1857
Aft transfer L	292.3	1900	2000	10.4393
Aft transfer R	292.3	1900	2000	10.4393
Wing L	323.1	2100	2200	11.5393
Wing R	323.1	2100	2200	11.5393
Total	2800	18200	19000	100

V-22

Figure 10 shows a schematic of the aircraft fuel tanks.

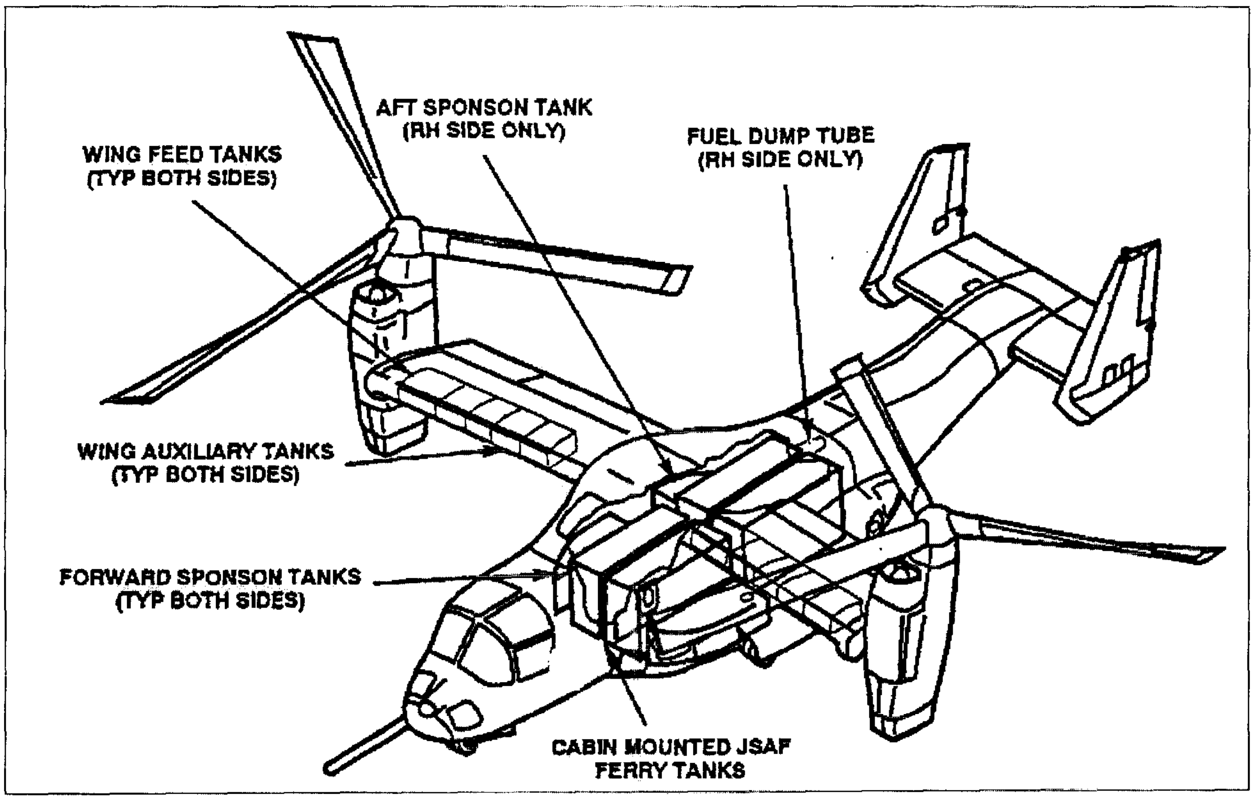


Figure 10. V-22 Aircraft Fuel Tank Schematic

Table 7 shows the aircraft fuel tank capacities.

Table 7. V-22 Fuel Tank Capacities

Tank	Gallons	lb. JP-5	% Total*	% Total**
wing engine feed tank (1)	97	660	4.8	2.2
wing engine feed tank (2)	97	660	4.8	2.2
left forward sponson tank	464	3155	23.1	10.5
right forward sponson tank	464	3155	23.1	10.5
auxiliary tanks rt (1)	73.5	500	3.7	1.7
auxiliary tanks rt (2)	73.5	500	3.7	1.7
auxiliary tanks rt (3)	73.5	500	3.7	1.7
auxiliary tanks rt (4)	73.5	500	3.7	1.7
auxiliary tanks lt (1)	73.5	500	3.7	1.7
auxiliary tanks lt (2)	73.5	500	3.7	1.7
auxiliary tanks lt (3)	73.5	500	3.7	1.7
auxiliary tanks lt (4)	73.5	500	3.7	1.7
rt aft sponson tank	300	2040	14.9	6.8
internal ferry tank (1)	602	4093		13.6
internal ferry tank (2)	602	4093		13.6
internal ferry tank (3)	602	4093		13.6
internal ferry tank (4)	602	4093		13.6
Total Usable Capacity	4418	30042	100	100.0
Total without internal ferry tanks	2010	13670		

* Does not include internal ferry tanks
** Includes internal ferry tanks

Commanche

The Commanche (RAH-66) helicopter main internal fuel (basic A/C version) has one 300 gallon fuel tank. Auxiliary tank kits are being planned.

Helicopters

Typical helicopter fuel tanks are approximately square or rectangular in shape, holding about 20 to 50 gallons of JP-4 fuel, supported by sandwich honeycomb or reinforced aluminum structure, and lined with rubberized material or self-sealing crashworthy bladders. Helicopter fuel tanks incorporating these bladders have shown increased tolerance for ullage explosion overpressures. Helicopters usually fly at low altitudes and have relatively low climb and decent rates as opposed to fixed wing aircraft that have substantially different fuel systems, flight profiles and fuel types. [2]

3.1.3.3 Overview of Platform Fuel Tank Operating Environments

Table 8 provides an overview of the selected platform fuel tank operating environments.

Table 8. Overview of Platform Fuel Tank Operating Environments

NGP PLATFORMS	TEMPERATURE	PRESSURE	MAXIMUM OVERPRESSURE (STRUCTURAL LIMITS)	FUEL TYPE	CURRENT INERTING SYSTEM
C-130	-80°F to 160°F	Up to 30,000	7 psig	JP-8	in tank foam
C-17	Up to 30,000	Up to 30,000	7 psig	JP-8	OBIGGS (molecular sieve type)
F-16	-65°F to 180°F	3 psig	16 psid	JP-4/8	Halon 1301; may be going to CF_3I
F/A-18	-65°F to 180°F	3 psig	20 psig	JP-5/8	In tank foam; self sealing tanks
CH-47	160°F (maximum) 135°F (bulk fuel temperature)	1.5 psi	CH-47 (5 psi – due to weak inner wall) MH-47 (30 psi)	JP-4/5	OBIGGS (for the Special Operations version)
H-60	160°F (maximum) 135°F (bulk fuel temperature)	1.5 psi	25 to 30 psig	JP-5/8	none
OTHER PLATFORMS	**TEMPERATURE**	**PRESSURE**	**MAXIMUM OVERPRESSURE (STRUCTURAL LIMITS)**	**FUEL TYPE**	**CURRENT INERTING SYSTEM**
F-22	-65°F to 180°F	3 psig	20 psig	JP-8	OBIGGS (permeable membrane / hollow fiber type)
F-117	-65°F to 180°F	3 psig	20 psig	JP-4/8	Halon 1301; going to OBIGGS
V-22	160°F (maximum) 145°F (bulk fuel temperature)	1.5 to 2.5 psi	7.5 to 10.2 psig	JP-5/8	OBIGGS (molecular sieve type)
Commanche	160°F (maximum) 135°F (bulk fuel temperature)	1.6 psi	45 psi (fuel cell bladder) (derived from 65 foot drop test requirement)	JP-5/8; JP-4 (cold starts)	OBIGGS (molecular sieve type)

Shaded regions indicate estimates based on similar aircraft type.

3.2 REVIEW OF ALTERNATIVE TECHNOLOGIES AND ASSESSMENT OF CURRENT STATUS

A literature search of previous efforts was performed that included a search of the SURVIAC and DTIC databases, a review of recent Federal Aviation Administration (FAA) reports (generated as a result of the TWA-800 incident), a review of the Bureau of Mines information, and a review of information from the Gas Research Institute. A list of these reports is given in Appendix A. Reactive and active (pre-protection) systems will be discussed.

3.2.1 Reactive Systems

The reactive systems discussed in this report include: LFE, PRESS, SCS, NIBBS, and technologies developed by Pacific Scientific and Primex Aerospace Corporation, Bureau of Mines, the Gas Research Institute, and Zvezda.

3.2.1.1 Linear Fire Extinguisher (LFE)

The linear explosion suppression approach is not new. Both the Air Force and the Bureau of Mines have tested similar concepts as early as 1969. From the early Air Force work, the concept of active ullage explosion suppression was considered feasible. However, at that time, the optical detection capabilities were not sufficient to make the system work reliably. Recent tests of active systems have capitalized on sensor advancements since 1969 and have used high-pressure storage bottles with elaborate manifold systems to discharge extinguishant throughout a fuel tank. The success of this configuration is dependent on its ability to disperse the extinguishant into the ullage expeditiously enough to suppress a developing explosion. This was a weakness of reactive systems tested in the past. The use of the linear distribution system has eliminated the manifold's time-critical discharge problems and has provided a system that theoretically could deliver the stored extinguishant in time to suppress a developing explosion. [9]

The LFE is a detector-suppressor protection system with a unique feature; it uses linear shaped charges to disperse the extinguishant. Though initially developed for dry bay fire suppression in conjunction with IR detectors, it was soon realized that this unique storage/distribution system possessed advancements that would enable the LFE to perform as a reactive ullage explosion suppression system.

John E. Lindberg was the inventor of the pneumatic linear fire detector. Systron Donner bought the John E. Lindberg Company. They then sold to Whittaker Safety Systems and in turn Whittaker sold them to Meggitt Safety Systems. It was and tested by the Naval Weapons Center (NWC). Their test program verified the consistency and effectiveness of this new design approach to ullage explosion protection. [1]

The LFE explosion suppression system was designed in response to a military request for proposal in 1985 for dry bay protection against API and high explosive incendiary (HEI) threats. Original requirements were for aluminum oxide powder as the suppressant, but testing showed this to be a poor requirement. A halon system using a tubular container design was specifically aimed at the wide area dispersal and quick response needed. Later development of this system utilized Halon 1301 in a long tube and released by a small linear shaped charge externally attached to the tube wall axially, dubbed the linear fire extinguisher, LFE. A dual-spectrum optical sensor detects fuel ignition and the controller reacts by triggering a small explosive initiator that ignites the shaped charge attached to the storage tube.

Testing was successful against the normal range of external threats and the LFE was the first system to demonstrate any protection against the 30mm HEI threat. [10]

Description/Types

The LFE system consists of an optical sensor (either discriminating or non-discriminating), a hollow thin-wall stainless steel tube for extinguishant storage, and a combination detonator and flexible linear shaped charge (FLSC) for extinguishant discharge initiation. The size, quantity and placement of these components are determined by the number, configuration, and proportions of the fuel tanks and adjacent dry bays requiring protection. [9] Figure 11 shows the LFE system.

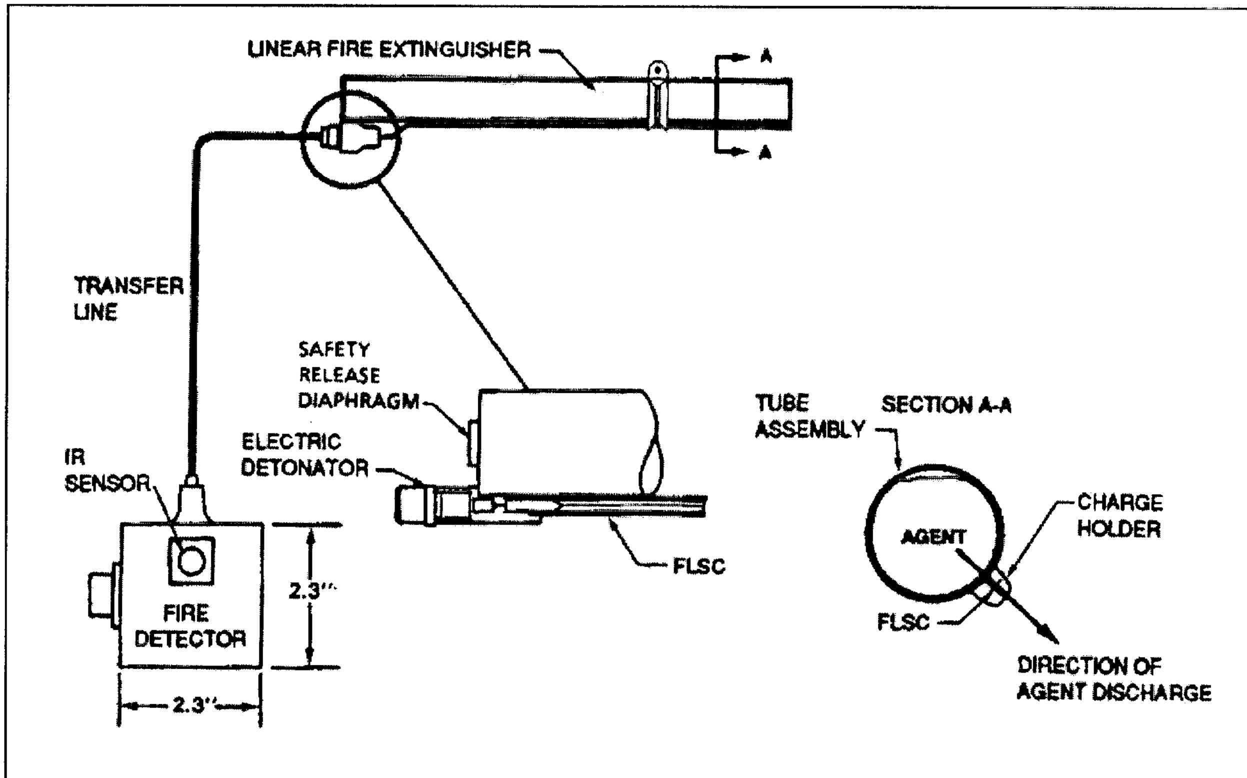


Figure 11. LFE System

The LFE consists of stainless steel tubing with stainless steel end caps welded to each end, forming hermetic joints. One of the end caps contains an integral pressure switch and a relief valve. The charge holder is designed to support the metal sheathed FLSC at the correct stand-off distance from the steel tubing to obtain its optimum cutting ability. The stainless steel tube is then charged to a high fill density of the selected extinguishing agent and pressurized with nitrogen and helium to 500 psi at 70°F. Either or both ends of the charge holder terminate in a threaded detonator housing that accepts an electrically initiated 1 amp/1 watt no-fire detonator. Actuation of the detonator initiates the FLSC, which detonates and cuts open the stainless steel tubing at a rate of approximately 20,000 ft/sec. A 5-foot length of tubing, for example, would be cut open in less than ½ millisecond with almost instantaneous release of the pressurized agent. [1]

The LFE system operates as follows. When the optical sensor detects the developing explosion or fire, it initiates the detonator (via an electrical pulse), which in turn initiates the FLSC. The FLSC detonates, directing a shock wave and ultra-high-pressure plasma "jet" along the length of the tube forming the primary cutting action that opens the tube. The superpressurization extinguishant is then pushed out of the opened tube, filling the protected compartment and interacting with the developing combustion process to suppress the explosion or extinguish the fire.

Capabilities And Limitations

A ballistic test series was conducted to evaluate the potential use of the LFE as an ullage explosion suppression system and expand on earlier dry bay fire suppression testing. A 10 ft^3 wing fuel tank simulator and a 30 ft^3 fuselage fuel tank simulator were used for explosion suppression testing. [9] The primary threat in over 60 percent of these tests was the 30 mm HEI projectile. Halon 1301 was extremely effective in suppressing 23mm HEI initiated events but the higher energy density and hence higher temperature created by a 30mm HEI projectile caused the Halon 1301 to pyrolyze and added to the pressure rise. In the case of the 30mm HEI tests, Halon 1301 was completely ineffective, even in concentrations over 20 percent. Interestingly, however, the addition of small amounts of water was shown to surpass the Halon 1301 performance and was able to minimize the fuel tank overpressures to less than 20 psig, even with the 30mm HEI threat. [1] Limited testing with the .50-cal API, 12.7-mm API and 23mm HEI was also conducted. [9]

The LFE provides uniform distribution along the whole length of the LFE. [1] The LFE expulsion rates were considerably greater than traditional bottle storage extinguishing systems. [9]

Operation of the FLSC in the LFE does not generate unacceptable hydrodynamic ram pressures when operating below liquid fuel. [1] However, it does create a challenge because of the shock loads transmitted into the structure through the mounting brackets.

Projectile-induced ullage explosions are usually generated by a specific sequence of events. The elapsed time from threat impact to a fully developed explosion occurs within milliseconds. The LFE system, initiated by projectile function or fragment impact flash, operates within the same millisecond time frame and is expected to create a "protected" ullage space before damaging overpressures are developed from the ensuing explosion. The parallel explosion-development/LFE system-activation sequence is as follows: [9]

- Projectile penetration causes an incendiary flash and the subsequent detonation disperses incandescent particles and fragments within the threatened fuel tank, beginning the process of explosion development.
- Optical sensors respond to the incendiary flash, triggering a detonator to activate the extinguisher(s).
- The extinguisher(s) discharges an explosion inhibitor that suppresses the explosion, thus negating development of damaging overpressures.

Various means of optical detection were used. The response showed that the LFE was open and discharging its contents in less than 1 millisecond. [1] Detection of small caliber threats should be the driving factor for design of sensor installation configurations. Suppression of HEI generated explosions/fires should be the driving factor for design of extinguisher installation configurations. [9]

The LFE approach for ullage protection appears especially suitable for large fuselage cells. [1]

Variations in the LFE system performance can be obtained by altering parameters such as the superpressurization value, agent type, agent weight, and LFE orientation.

A reactive explosion suppression system is feasible, but dependent on the suppression agent used. [9] Some of the extinguishing agents tested were distilled water; aqueous film-forming foam (AFFF) and water solution; water, AFFF, and Halon 1301; water and monoammonium phosphate powder; 30 percent calcium chloride and water solution; 50 percent ethylene glycol and water solution; 70 percent ethyl alcohol and water solution; Halon 1301 and water mixture, propane; and monoammonium phosphate powder mixed with Halon 1301. These agents absorb thermal energy from the explosion within the millisecond time frame to prevent fuel tank damage caused by overpressurization. [11] Halon 1301 can be an effective explosion suppression agent against .50-caliber AP rounds when used in compartmentalized structures such as wing tanks. Halon 1301 works well for all threats up to and including 23mm HEI. It is does not suppress a 30mm HEI unless it is used in conjunction with a coolant such as water or an aqueous solution, etc. Incidentally, aqueous solutions introduce the potential of corrosion and contamination into an aircraft's fuel system which is viewed with great concern by all aircraft manufacturers. Water and monoammonium phosphate powder used in an active suppression system is capable of limiting HEI threat induced explosion overpressures in large volumes. [9] A limitation of this system is that it is a "one-shot" system in which the distribution system destroys itself in its operation. [2]

A later test phase was performed to evaluate the LFE system's ullage explosion suppression performance using water-based suppression agents as well as collect data that would expand on earlier explosion suppression tests. Eight different agents or mixtures of agents that fell into three broad categories were used for suppression testing. The mixture of the ninth agent, water and ethyl alcohol proved to be flammable under the test conditions and was not evaluated as a suppression agent. The three categories were nonwater-based agents, water-based agents, and combinations of water-based and nonwater-based agents. [11]

LFE extinguishers containing the following agents successfully suppressed ullage explosions: water/halon/AFFF, water/AFFF, halon/MAP, and propane. Additionally, optimum or minimum weights of agent required for protection per cubic foot of ullage were defined for the water/AFFF and water/halon/AFFF agents. The addition of AFFF to water significantly improved the explosion suppression capability of the agent. Equivalent weights of the lowered freezing point aqueous solutions ($CaCl_2$ brine) are much less effective than the water/AFFF mixtures. Examination of the trends of the water/AFFF tests and the water/halon/AFFF tests indicates that, for a particular ullage size and configuration, an optimum weight of suppressant agent is present that will provide the best protection. Greater agent weights provided no additional protection, and may have resulted in less suppression than lower agent weights. Examination of the results of the halon/MAP tests indicates that these agents can be as effective as the water/AFFF or water/halon/AFFF, but no data on an optimum weight of agent were obtained. One of the most effective agents tested was 0.2 pound of water/halon/AFFF per cubic foot of ullage. These tests met or exceeded our goal of limiting ullage pressures to 10 psig. A weight of 0.2 pound appears to be optimum for the agent mixtures tested in the simulator used. The most weight-effective agent tested for the weight penalty that it would incur was Propane. Propane at 0.07 pound of propane per cubic foot of ullage met or exceeded our goal of limiting ullage pressures to 10 psig. [12]

The most recent LFE test series examined four agents (FC-218, HFC-227ea, HFC-125, and pentane) alternate to Halon 1301. Each of the four agents was discharged from LFEs. FC-218, HFC-227ea, and HFC-125 extinguish fires through a combination of chemical and physical mechanisms. Generally, these fire and/or explosion suppression agents rely on chemical action to inhibit combustion, thus suppressing an explosion. The physical mechanism primarily involves extinguishing flames by increasing the strain rate or flame stretch. An ullage explosion initiated by a 12.7-mm API required roughly twice as much of the above three agents by mass fraction to achieve a level of suppression similar to that of pentane discharged from LFEs. Pentane forces the fuel-to-air ratio in the ullage beyond the rich limit, smothering the combustion process. It seems that the fuel-enriching mechanism is more efficient than the chemo-physical mechanism inherent in the FC/HFCs, at least for the test conditions used in this study.

Threats used during testing were the single 110-grain fragment, the 12.7-mm API, and the 23-mm HEI. Halon 1301 was not tested under this test series.

Partial suppression only was realized against the 12.7-mm API in all tests of FC-218, HFC-227ea, HFC-125, and pentane as discharged from LFEs. Partial suppression resulted because of hardware constraints that limited the maximum amounts of agent that could be discharged. The greatest concentrations of agents tested were as follows: FC-218, 38.8% (67.3% mass fraction); HFC-227ea, 42% (66.9% mass fraction); HFC-125, 52.5% (64.4% mass fraction); and pentane, 37.5% (47.8% mass fraction). Testing of several amounts of each agent allowed definition of the effect of agent concentration and mass fraction on peak pressure in the simulator.

Of the agents tested in this series, pentane performed better than FC-218, having the best suppression efficiency based on agent concentration. The performance of FC-218 was followed by HFC-227ea and then by HFC-125. Comparison of peak explosive pressure as a function of agent mass fraction revealed that the amount of pentane required to achieve the suppression level of FC-218, HFC-227ea, and HFC-125 was about 70% of the amount needed for the other three agents. Under certain conditions, HFC-125 was found to increase ullage pressures by acting as an additional burning agent and thus was not considered for the active ullage-suppression systems testing. [13]

Some advantages and disadvantages of the LFE system include:

- Advantages:
  - Speed (response within 5 milliseconds),
  - Suppressant speed – 1000 ft/sec,
  - Efficient distribution, and
  - Low weight (mostly suppressant).
- Disadvantages:
  - Power consumption,
  - Detector technology lags,
  - Ullage overpressure with halon, and
  - Reaction forces from tube. [14]

Weight And Cost Implications

System weight will depend on the size and shape of each fuel tank. Systron Donner has built and tested LFEs with outside diameters of 1.0 and 1.25 inches, which allow some freedom in optimizing agent concentration within a variety of tank configurations. [1] Since the concept of the LFE allows any physical length of tubing to be used, it is not limited in length sizing. However, long tubes mean more FLSCs and therefore more shock loading into structure. It is necessary that the container be sized in diameter according to the amount of suppressant needed to protect the volume of the tank being considered; the greater the container diameter, the greater the resulting volume of suppressant to be released. Due to the pressurized nature of the container, the volume of fuel displaced by the suppressant storage system is minimized. A comparison of weights, provided by Whittaker, of the tubular storage systems to other protection systems (rigid foam, N_2 inerting, halon inerting, Scott Foam, etc.) show the tubular storage system to be the lightest system per unit volume protected. Specific weights are dependent on the detailed requirements and the configuration of the installation being evaluated. [10]

Cost will therefore be somewhat dependent upon the tank's configuration and its internal complexities. [1] Only rough order of magnitude costs of procurement, shown in Table 9, have been evaluated. [10]

Table 9. Estimated Linear Fire Extinguisher System Component Costs

Whittaker Safety Systems - LFE® Suppressant System

FUEL TANK PROTECTION SYSTEMS
Rough Order of Magnitude
SYSTEM COST MATRIX SUMMARY

AIRCRAFT TYPES (MTOGW - MLW)	PROJECTED NUMBER OF TANKS	FUEL VOLUME (US GAL)	PROJECTED NUMBER OF DETECTORS	DETECTOR COSTS	PROJECTED NUMBER OF EXTINGUISHERS	EXTINGUISHER COSTS	TOTAL COSTS
LARGE (800K - 600K)	5	54,000	10	$15,000	30	$24,000	$39,000
MEDIUM (330K - 270K)	5	24,000	10	$15,000	20	$16,000	$31,000
SMALL (160K - 130K)	3	4,000	6	$9,000	12	$9,600	$18,600
REGIONAL T/FAN (76K-69K)	3	3,200	6	$9,000	6	$4,800	$13,800
REGIONAL T/PROP (40K-38K)	2	1,400	4	$6,000	4	$3,200	$9,200
LARGE BIZJET (35K-30K)	3	2,000	4	$9,000	6	$4,800	$13,800

Effects On Other Aircraft Parameters

The detonator has a definite service life. The predicted life from the date of manufacture is 10 years, which consists of up to four years of storage and six years of installed service. As a result, the detonators will require replacement just before their service life expires. [1]

Activation of this system with maintenance personnel in the tank presents a hazard of serious injury. Positive and appropriate deactivation procedures, as when handling ejection seats and missiles, must be incorporated prior to entry into a tank equipped with this suppression system.

The only range impact would be carrying the additional weight of the system. [10]

Possible effects on flight safety, crashworthiness, and other capabilities are unlikely but as yet unknown. [1]

Current Status

Further testing is required to determine the compatibility of the suppressant with the environment and the fuels requiring protecting, especially considering alternative suppressants. Testing must address the concerns associated with potential overpressures, the effects of discharging the LFE when completely submerged in fuel and the ability of successfully dispersing the agent into the fueled areas.

Further design and development work is necessary to understand and to minimize the reactive loads that are imposed on the aircraft structure when the LFE is discharged. The testing to date has not shown these loads to be a structural problem, but the nature of high magnitude, impulse loads requires a dedicated look at the potential effects.

A certification program is required to address the complete installation and operation of the finalized system. [10] Although this concept has not been developed to flight hardware, it is not because of a lack of testing technology, but the inability to develop the protection concept itself to a reliable, affordable system. [2]

Testing has shown this technology to be very effective, with the shortest reaction times of any investigated. However, further development is necessary to define a system adequately compatible with the closed fuel tank and variations in ullage volume.

Testing to address the concerns of overpressures must be conducted. Pyrotechnic devices in aircraft fuel tanks present a potential risk to the aircraft. A full safety analysis would be required to evaluate the resulting level of safety of the aircraft. In the case of this suppression system, a discharge of the system would release an explosion / fire suppressant into the fuel tank and reduce any threat due to fire or explosion. [10] The reaction loads of some of the systems on the tank structures on which they were mounted caused enough damage to bring into question the flightworthiness of the structure after the system is fired. [2]

Discussions with Government personnel indicate that a LFE test program is scheduled to be performed the summer of 2000 at Wright-Patterson AFB, Ohio, Aircraft Survivability Research Facility (ASRF). [15]

The upcoming test program will not only address the LFE, but will also attempt to characterize the reactive loads applied to the aircraft structure as a result of LFE activation. During the original tests, the loads occurred so quickly that they were not captured by the instrumentation. The effects were also not obvious due to the robustness of the test article used. However, when the system was tested on an aircraft structure, the reaction load effects were evident. Some "quick fix" methods were attempted to mitigate the reaction loads. These included the use of shock absorbers (but the natural frequency was too low) and putty. With the upcoming testing, these reactive loads will be quantified, if possible. In possible later studies, methods to mitigate these loads will be explored.

For the upcoming testing several agents may be tested and include CF_3I and a fuel (propane or butane). The alternate agents have not been selected because they are awaiting information on the chemical reaction rates of the agents to determine whether the agent will be able to respond in time. The threats will include 12.7 mm API and 23mm HEI. [16]

3.2.1.2 Parker Reactive Explosion Suppression System (PRESS)

Another system similar to the LFE system is the Parker Reactive Explosion Suppression System (PRESS).

Description/Types

The Parker Reactive Explosion Suppression System (PRESS) is designed to be installed in aircraft fuel tanks and react to and suppress fuel tank explosions. It consists of an optical detector, transmission lines and a suppression tube(s) containing a water/brine solution. This system is designed to respond within a few milliseconds to engage the flame front and reduce pressures below damage causing levels. After detection, the transmission lines transmit a signal to the suppression tube, which initiates an exploding bridgewire circuit. This, in turn, initiates a detonating cord and propellant internal tube, creating a high pressure expulsion force to expel the adjacent bladder filled with water. The water exits through orifice holes, is transmitted through radial channels in the external nozzles and released as 5-micron-thick sheets. These sheets break up into 10-micron droplets that absorb thermal energy released by the explosion. This process occurs in its entirety within a few milliseconds.

Several factors lead to the selection of water as the suppressant. Water has the highest heat of vaporization and specific heat of any material. It is weight and volume efficient, as well as cost efficient. Despite water's advantages, it must not be frozen when it is to be used. Dissolving 31.4 percent by weight calcium chloride ($CaCl_2$) in water reduces its freezing temperature to below –65°F. It is, incidentally, the only salt which depresses water freezing temperature to below –65°F and antifreeze such as glycol, glycerol, and alcohols are unacceptable because they are fuels. Parker has conducted tests on 31.4 percent $CaCl_2$ brine down to –75°F and up to 160°F (within the aircraft operating environment), and no adverse effects were found. The effect of temperature was entirely reversible with no precipitation of salts, and there was no volume change upon freezing. The corrosion implications of introducing a chloride salt into a fuel tank was considered and found to not be a significant problem as discussed below. The volume of water required for protection is 0.05 percent.

PRESS (shown in Figure 12) consists of a light-activated explosion sensor and tubular suppressant storage-dispersion vessels interconnected by coax cables for each tank. The aircraft electrical system supplies power to the sensors. When the system is activated by supplying electric power to the explosion sensor, a built-in power supply charges the capacitor to its operating voltage, typically 2,500 volts. When light is detected, the over voltage spark gap is actuated. This discharges the capacitor through coax cables to the exploding bridgewire (EBW) in each dispersion tube within a microsecond after the light detection signal is sent. This activates all EBWs, which in turn initiates the propellant cord fuses. The detonation velocity of the fuse is over 20,000 fps, or 50 microseconds per foot, which means the functioning of the fuse will reach the ends of a 6-foot dispersion tube within 150-microseconds.

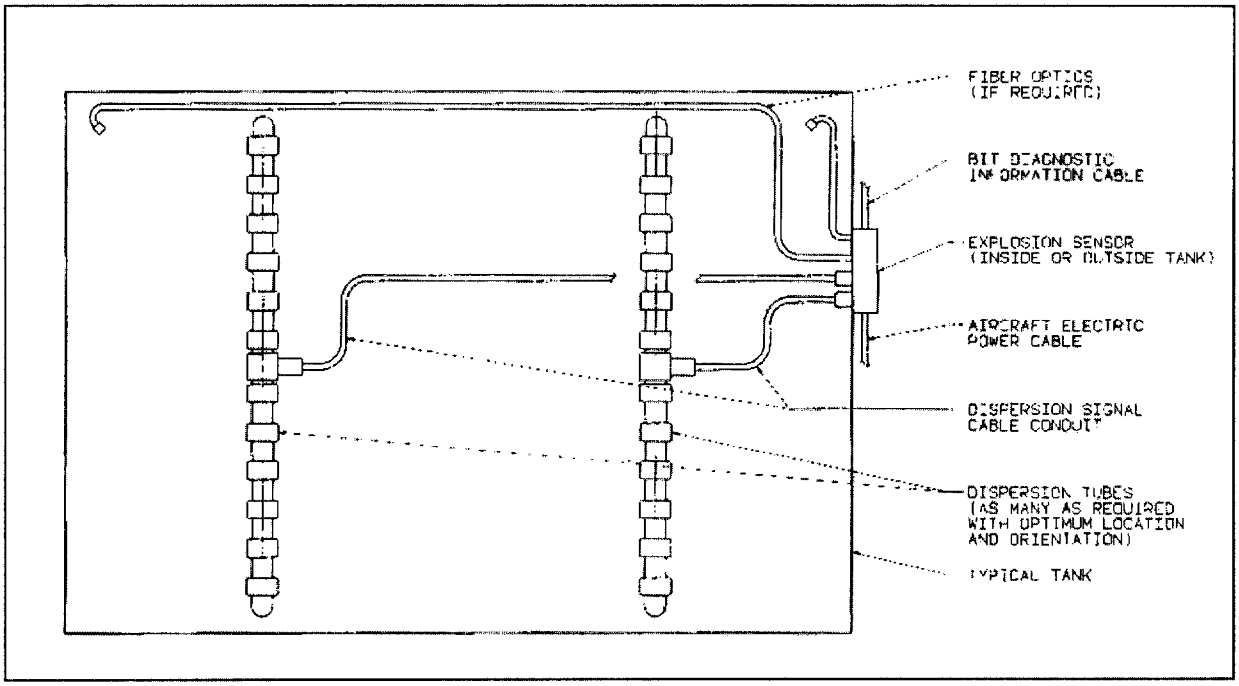


Figure 12. PRESS System Arrangement

When the fuse is activated, the chemical propellant ignition starts virtually instantaneously along its length. The propellant pressure applies to the outside of the bladder and raises the suppressant pressure. This produces pressure across the unsupported areas of the bladder that lie over the discharge orifices in the casing. These sharp edged orifices are sized so that when the suppressant pressure exceeds 20,000 psi, the bladder is sheared through the orifices like burst disks. This starts the flow of suppressant, while the suppressant pressure continues to rise rapidly to a peak, typically below 30,000 psi.

As the suppressant is discharged, the bladder wall between the propellant and suppressant provides a membrane that separates burning propellant gas from the suppressant. As the suppressant is expelled, the membrane follows the suppressant. When it is completely expelled, the propellant side of the bladder is doubled smoothly into the opposite half of the casing covering the discharge orifices and closing them off. As the suppressant is discharging, the propellant pressure continues to decrease because of increasing volume and cooling of propellant gas. It reaches a few thousand psi in 10 to 15 milliseconds, depending on the quantity of suppressant, the suppressant flow restriction, and the propellant used. By this time, the propellant pressure is low enough that the propellant side of the bladder wall will not shear through the orifices a second time. Thus, the propellant flame and products of combustion are isolated from the tank. This means of opening and reclosing discharge orifices will be recognized as an inherently high reliability valving method.

The suppressant discharge flow path is sized so a small fraction of the propellant pressure is consumed by flow pressure drop. This means a large fraction of the pressure is converted to kinetic energy in the suppressant discharge jets. Considering the brine specific gravity, a 20,000-psi velocity head produces a suppressant jet velocity of over 1,500 feet per second or 1.5 feet per millisecond. This means, if 0.25 millisecond is allowed to get started, the initial suppressant can be delivered anywhere within a 2-foot radius of the dispersion tube within the 2-millisecond time target by maintaining a 1.15 foot per millisecond average penetration velocity. How the direction and the high velocity penetration of the suppressant jets are controlled is discussed below.

Suppressant must also be delivered in a form that will react with the flame fast enough to control a stoichiometric mixture of burning gas. Since the approach involves cooling the reaction, it is necessary to absorb energy faster than the flame is releasing it. Conventional spray nozzle concepts are not suitable for this application. They produce a spray in which the droplet sizes tend to follow a bell curve with a small proportion of larger droplets containing most of the mass. This is counterproductive.

The nozzle design requirements for this application include:

- Compatibility with a tubular storage vessel which releases suppressant on one side with up to 30,000-psi peak operating pressure,
- Production of uniform, extremely small droplets of pre-determinable diameter,
- Production for controlling the direction of the suppressant jets to suit any tank shape—up to 360°,
- Provision for controlling the depth of penetration of high velocity suppressant jets to suit any tank shape, and
- Promotion of high velocity mixing of suppressant droplets with ullage gases.

Parker has a patented nozzle that was specifically designed to meet these requirements. It is a cylinder that slips over and seals to the dispersion tube casing covering each group of discharge orifices. It consists of a cylindrical body with an inside diameter larger than the dispersion tube and two end rings that seal to the casing. Thus, there is an annular passage between the casing and the cylinder.

The cylindrical body is made up of a stack of washers. Each washer has a pattern of channels impressed into one side. There are radial channels leading from the inside diameter of the washer to a circumferential channel next to the washer outside diameter. A narrow outer rim separates the circumferential channel from the washer outside diameter.

When the washers and end rings are stacked and brazed together, they make a cylinder which has multiple radial flow paths leading from inside to multiple circumferential channels adjacent to the outside wall of the cylinder. These channels have flow areas large enough to provide relatively low pressure drop flow paths. If the outer rims of the washers are depressed 0.0002 inch below the washer surface, when the washers are stacked together there will be a 0.0002 inch slit in the outer surface of the cylinder between each washer.

With nozzles in place, there is a relatively low pressure drop flow path from inside the casing through the discharge orifices, through the annular passage and the radial channels to the circumferential channel and then out through the slits. When the discharge orifices are sheared open, sheets of suppressant will emerge from the slits at extremely high velocity. Surface tension and turbulence will quickly break the sheets into droplets. The diameter of the droplets will theoretically be twice the thickness of the sheet. Thus, a 0.0002-inch slit, which is 5 microns, will produce 10-micron droplets, and their size will be uniform. The slit width can be varied by design to determine droplet size.

The direction of the suppressant jets can be controlled to suit the tank configuration by providing the depression in the outer rim only at the location on the nozzle cylinder from which the jets should emerge. Thus, the jets can discharge over 360° for a nozzle installed vertically in the center of a tank, or over 180° for a nozzle installed at the top of a tank, or in opposite directions with narrow fans for shallow tanks.

The question of contamination of such narrow slits is a valid concern. Protection from contamination from the outside will be provided by a frangible sleeve over the outside diameter of the nozzle covering the slits and sealed to the end rings. It will be popped open by the initial high pressure suppressant discharge. Protection from contamination from inside will be provided by filling the bladders with particle clean suppressant. This will not be a problem with controlled manufacturing conditions because each nozzle will only pass a few cubic inches of suppressant during its one-time operation.

One of the critical nozzle design requirements is to be able to control the depth of penetration of high velocity suppressant jets to suit tank shape. High-speed suppressant jet velocity must be maintained well into the ullage to reach the flame in time. But high velocity must be dissipated before the jets reach a tank wall to avoid throwing suppressant out onto the wall when the jet stream is turned. As long as suppressant droplets remain suspended in the ullage gas, they are available to absorb energy to contribute to cooling of hot gas from the first ignition or to provide inerting for a second hit. The nozzle configuration provides two means for tailoring the depth of high-speed penetration into the ullage.

The primary means of controlling depth of penetration is called "flying wedge action." When a single sheet of 10-micron droplets is injected into an ullage, it will entrain air from both sides and be slowed in a short distance by transfer of momentum. When there are three sheets of propellant droplets produced by three closely spaced nozzle slits, the outside sheets will protect the flanks of the inside sheet for a short distance, so it will maintain its velocity further into the tank. If there are 10 or 30 adjacent slits in the nozzle, high-speed penetration will reach further into the tank, but then will stop off relatively abruptly when the center sheet is exposed.

Another means to affect the depth of high-speed jet penetration and throw-out onto the tank wall is to control the droplet size. The area of suppressant establishes the upper limit on suppressant droplet size. The area of suppressant needed for energy absorption required to exceed the rate of energy release by the fire establishes droplet size. Below that limit, the drop size can be optimized to affect jet penetration and throw-out. For a given suppressant flow rate, reducing droplet size will have two effects. It will increase entrainment of ullage gas to shorten penetration distance. It will also reduce the mass to frontal area ratio of the drops so the entrained air in the jet stream can produce a higher turning acceleration to prevent throwing droplets out of the stream onto the tank wall.

The number of washers per nozzle, the droplet size, and the spacing of the nozzles along the dispersion tube provide means for controlling the jet streams of entrained ullage gas so as to obtain the desired level of turbulent mixing within the ullage.

Capabilities And Limitations

The PRESS concept has been conclusively proven. The proof-of-concept tests have shown the system to successfully reduce the overpressure created by a 23mm HEI simulator detonated within an explosive propane air mixture in an experimental tank. Although optimization of the nozzle configuration was not fully attained, ullage pressure that would have reached 100 psi in 10 milliseconds, when not suppressed, was limited to below the objective during three tests. The PRESS approach showed it is possible to react fast enough to control the ullage pressure rise caused by simulated HEI ignition of a stoichiometric fuel vapor-air mixture. Although not enough empirical data were developed to fully understand the suppression process, it was shown that the process response to nozzle configurations is repeatable. [3]

Some advantages and disadvantages of the PRESS system include:

- Advantages:
  - Fastest responding system – allows less suppressant, lighter weight,
  - System designed for liquids like water – greater potential,
  - Tank overpressure problem not evident, and
  - Nozzles allow directed flow of suppressant.
- Disadvantages:
  - Requires large scale proof-of-concept testing,
  - More complex system – chance for malfunction despite high reliability components, and
  - Possible expense in manufacture. [14]

Weight And Cost Implications

Advantages of dual slit nozzle configurations were recognized. There are indications that the speed of delivery of initial suppressant into the fire is not as critical as originally thought. This confirms a potential for reducing projected system weight. [3]

"Ball park" cost estimates were performed and showed that the system would be fairly expensive. [17]

Effects On Other Aircraft Parameters

The PRESS approach leads to inherent reliability, minimum weight, and minimum operational support. The equipment is mechanically nonactive, simple, and rugged, as well weight efficient. When protection is required, the least number of series functions are involved, and the functions are simple. Solid-state electronic built-in-tests automatically monitor all inspection requirements. The only new technology in the system relates to means for ultra-fast suppressant dispersion.

Reduced life cycle costs will result from elimination of consumables and from the characteristics of PRESS equipment. Service cost and maintenance for the life of the fleet will be reduced. Procurement cost and handling of consumables will be eliminated. Equipment for a closed fuel tank vent system is not required. Compared to foam in large aircraft, savings of fuel cost to carry the system weight will be significant, and in addition, there will be cost savings in fuel tank maintenance because of simplified tank access. Further, cost of equipment procurement and installation will be relatively low. In addition, improved weapon performance will result from low airborne weight and use of no compressor bleed air.

Improved operational readiness will result from reduced system down time, elimination of between sortie servicing, and elimination of logistics for consumables. Compared to foam, unobstructed access to fuel cells will reduce fuel system downtime for maintenance. Retrofit into existing aircraft is feasible because the system can be designed to be installed entirely within fuel tanks, through existing tank access doors. Electrical wiring, for standard aircraft power and desired diagnostic information from the explosion sensor built-in-test, is all that is required outside of fuel tanks. Displacement of fuel will be less than 0.1 percent. However, brackets and electrical wiring may require fuel tank penetration.

When a new concept for ullage protection is considered, numerous areas of concern come to mind. Parker has addressed some of these concerns, which are summarized below with Parker's observations.

- Use of explosives and chemical propellants inside fuel tanks to suppress a fuel explosion initially causes concerns. The following facts should eliminate those concerns. First, the flame and propellant products of combustion are completely contained inside the dispersion tube with a high-level of assurance. Second, the technology for electro-explosive systems has matured during many years of service in crew ejection and rocket staging systems. Third, the system is protected from inadvertent discharge by use of secondary explosives in the EBW and propellant cord fuse. A secondary explosive fuse is used to ignite the smokeless powder propellant and an EBW detonator, which uses only secondary explosives, is used to function the fuse. The no-fire threshold voltage of the EBW is over 500 volts to prevent discharge by stray signals. The propellant and the secondary explosives in the fuse and EBW are mechanically and chemically highly stable.

- Independent redundant seals will be provided to assure the propellant will not be contaminated with fuel or moisture. The dispersion tube casing will be sealed with respect to the fuel tank ambient environment. The suppressant bladder will be hermetically sealed with respect to the inside of the casing. The propellant cord will be hermetically sealed with respect to the inside of the casing. Thus, there will be two independent seals between all sources of fuel or moisture and the propellant.

- Introducing water into a fuel system has raised concerns about the possible effect on engine operation. The design quantity of suppressant, one-tenth of cubic inch of water per gallon of ullage volume, is 0.05 percent by volume. This is a small quantity compared to worst case entry of water through vent systems during descent in a storm, which aircraft are designed to accommodate. Water would be introduced as an extremely fine, 10-micron spray, which will prevent it from collecting quickly at a tank fuel outlet. It therefore could not be injected into an engine fuel system as slugs of water.

- Introducing a chloride brine into a fuel system has also raised concerns about corrosion or possible effects on engine operation. It would only be discharged into a tank in response to battle damage which would need to be repaired, including clean-up. The probability of needing ullage protection is extremely low compared to, for example, an engine compartment fire where clean-up would be a larger factor in repair. It was suggested that the brine is not extremely corrosive, being rather like concentrated sea water. Also, the quantity is small and it is introduced as a fog, so that slugs would not be ingested into the engine as pointed out above. However, it should be noted that fuel tank components are not designed to handle corrosive materials. In fact aviation fuel is required to contain anti-corrosion additives to offset the corrosive nature of some of the aviation fuel components.

- Ultra-fast suppressant dispersion raises concerns about mounting bracket reaction loads. Reaction loads depend on several parameters including: peak discharge pressure, projected nozzle area, suppressant quantity and density, and discharge time. The effect can be indicated by specific examples. As one example, reaction was calculated for a single dispersion tube at the top of a 100-gallon tank, with a 180-degree spray angle, a 14-millisecond discharge time, and a 20,000-psi peak exit pressure. This magnitude of pressure may be required when an extremely fast initial suppressant velocity is needed for small tanks. The reaction at the instant of peak pressure would be less than 50 pounds per inch of tube. Since, with PRESS, the nozzle area is fixed, the thrust calculation is simple and precise. In one form of the expression, thrust equals two times the discharge pressure times the nozzle area. Another example indicates the effect of further increased time. If there is a tank twice the size of the one above with two similar dispersion tubes, and it is assumed that the pressure rise time is doubled because of the size and therefore the time to deliver the suppressant can be doubled, the reaction load for each tube would be reduced by a factor of four. This is because with twice the time to deliver suppressant, the jet velocity would be reduced by one-half. Since the required pressure varies as velocity squared, the discharge pressure would be reduced by four. The system weight would also be significantly reduced because the dispersion tube casing weight is directly proportional to pressure. Of course, when conditions are such that suppression can be effective with nozzles arranged to spray 360°, or in opposite directions, reaction loads will cancel. In tanks which are more than half as deep as the critical horizontal dimension, optimum orientation of dispersion tubes is likely to be vertical and centrally located with dispersion in opposing directions. Thus, reaction loads will be zero. With PRESS, the driving pressure is essentially independent of ambient temperature, so reaction loads don't increase with temperature. In larger tanks, reaction loads tend to decrease because, with the same ignition source, pressure rise time tends to increase. This means there would be more time to deliver suppressant and a corresponding reduction in required discharge pressure.

- PRESS will be inherently resistant to battle damage in several respects. The explosion sensor, which reacts to the light of the impact flash or the projectile detonation, can complete the discharge signal to all of the dispersion tubes in a tank within 10 microseconds, before fragments from a projectile detonation can travel more than an inch or so. After the discharge signal has been received, each dispersion tube will complete its discharge independently of the control system. The discharge casings will be partially protected by the thick walls of the nozzles that cover a significant fraction of the length of the casing. They will distribute fragment impact loads and tend to prevent failure of the casing so that other nozzles of the dispersion tube can continue to function. It also may prove wise to provide redundancy of dispersion tubes. Two dispersion tubes can replace a single dispersion tube with half the suppressant capacity with only a minor weight increase. It can be shown that for a given operating pressure and length, the weight of dispersion tube casing is proportional to the volume of suppressant contained. Thus, one dispersion tube can be replaced by two with no weight penalty in the casing that is the largest weight element. The weights of twice as many half-size nozzles and casing fittings represents a second order weight penalty. Further, with PRESS, the protection for each tank is independent of all other tanks in the vehicle. Thus, a hit in one tank does not negate future protection for other tanks, as is the case with inerting systems where inerting gas is supplied to all tanks in parallel and a hole in one tank can deplete the entire inertant supply.

- Discharge of suppressant when the dispersion tube is submerged in fuel can be expected to not produce a hydraulic ram effect. Discharge of suppressant distributed within the tank and the maximum velocity of the suppressant jets will be 1500 feet per second, whereas the velocity of sound in fuel is over 4,000 feet per second. Thus, the jets will not produce significant shock waves.

- Fuel tanks in operation will be closed to external light. A nondiscriminating explosion sensor is, therefore, desirable because of its simplicity and fast response time. The possibility of activation by electrostatic discharge from fuel sloshing within the tank can be eliminated by light filters and threshold settings. Tanks with overtank filler caps can be protected from external light by internal baffles. External light could, however, be introduced through tank access panels during fuel tank maintenance. It will be necessary, therefore, to deactivate the system when the tanks are open. The system can be deactivated by any of the various means compatible with weapon system requirements. A simple example would be the use of a landing gear load switch to remove power from the sensors upon landing. The circuit can be designed to bleed down the discharge capacitor and deactivate the system at any desired time and to automatically reactivate the system when power is resupplied. [3]

Another issue was the installation of the PRESS system in small compartments. The installation would be difficult and costly. Also detection would be difficult since the detectors were line of sight. [17]

Current Status

Discussions with Government personnel indicate that limitations in research funding prohibited demonstrating the effectiveness of PRESS for suppressions of fuel vapor explosions ignited by live fire incendiary rounds in a 100-gallon test tank at the Wright-Patterson AFB ASRF gun range. These discussions also indicated that the PRESS nozzle design was too complex and required very tight tolerances (which prohibited a low cost manufacture). To alleviate this problem, conventional nozzles were used in a radial fashion to generate the same effect. [18]

Parker Hannifin representatives stated that the PRESS technology has been shelved due to technical and funding issues. [17] However, their withdrawal does not mean that this system is "dead". Another manufacturer should "pick up the torch" and pursue this technology. The PRESS system is a patented system ("Explosion Suppression System", Bragg, K.R., Filed March 11, 1987, Patent Number 4,834,187). One potential avenue could include a patent licensing agreement with Parker Hannifin in the short term until the patent expires and the information becomes public domain.

The primary technical issue has been the nozzle design and its ease/cost of manufacture. It became evident that two types of nozzles are required for limiting overpressure (penetrating droplets—diesel type nozzle) and for preventing reignition (fog droplets—simplex type nozzle). Manufacturers (see Appendix D) of these types of nozzles should be contacted. Use of standard nozzles (such as conventional jet engine fuel nozzles) would provide cost savings since they are already manufactured items and are more than likely already flight-qualified.

3.2.1.3 Scored Canister System (SCS)

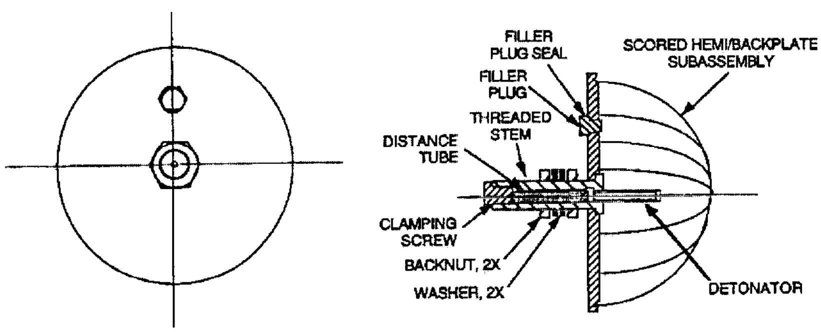
The research conducted on the original scored canister system (SCS) was prior to 1951. In 1954, a British patent was granted to Graviner Manufacturing Ltd. (now Kidde-Graviner). [10]

The canister type suppressor offered the unique feature of being able to be stacked on top of each other, so that the suppression system could be catered to each fuel tank system. A version of this design was used in a fuel tank ullage protection system for the F-105, the Buccaneer, the Canberra, and some U.S. Navy aircraft (which all used Halon 1011); plus the British aircraft Vulcan, Victor, Valiant, and Hunter aircraft (which all used pentane). While the suppression systems did not perpetuate into future suppression systems, the reasons were not because of their ineffectiveness; it was because the detection portion of the system was susceptible to false alarms. [19]

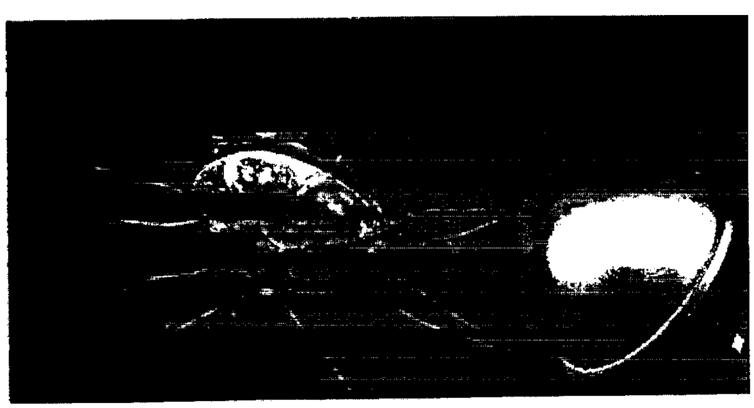
Field experience has been accumulated on the AVRO Vulcan, the Handley Page Victor, the Vicker Valiant and the Hawker Hunter, but the general data available does not provide a complete service history. This is the only 'operational' fuel tank ullage protection system uncovered in this technology investigation and as such, provides limited confirmation of the technology's overall success. [10]

Description/Types

The pentane filled SCS is designed to achieve suppression by creating a fuel-rich atmosphere in the ullage while avoiding fuel contamination resulting from use of a nonpressurized container. Figure 13 displays this device. Each SCS suppressor is composed of a scored, frangible hemisphere filled with a liquid-phase suppressant. The suppressor units are not pressurized and are suitable for operating under negative-pressure excursions within temperatures ranging from −35 to +60°C. The explosive device is carried at one end of a hollow stem that protrudes through the center of the unit's back plate. The explosive "blast" in the center of the liquid suppressant hydraulically couples to the scored frangible wall of the hemisphere, which fails along the score lines. The suppressor walls open within approximately 2.0 milliseconds (ms) of activation, and the explosive energy expels the suppressant as a cloud of spray, made up of fine droplets, that expands into the fuel-tank ullage.



(a) SCS schematic.



(b) SCS before (right), and after discharge (left).

Figure 13. Kidde-Graviner SCS

<u>Capabilities/Limitations</u>

This system was placed in service on a number of British military aircraft and has been documented as functioning satisfactorily and being credited with a number of 'saves' (suppressant discharges associated with actual ignition threats), though plagued with a large number of 'false alarms'. These aircraft were phased out of service in the late 1970s and early 1980s along with the suppression systems.

In developing this system, a number of suppressants were evaluated. Pentane and Halon 1011 were the two found to be superior suppressants. The use of Pentane should be examined in light of the potential of fuel tank rupture during a crash. Due to it s high vapor pressure, Halon 1011 requires a pressurized container.

The goal of the recent SCS testing was to determine the ability of four suppressors, each filled with 500 cc of pentane, to suppress an explosion in a flammable ullage ignited by impact with each of three threats: the 110-grain fragment, the 12-mm API, and the 23-mm HEI.

The peak pressures resulting from attempted explosion suppression using an SCS system in a flammable ullage are compared with the peak pressures of unsuppressed (no SCS) explosions. Total successes (i.e., positive suppression of the fire and/or explosion in the ullage) were realized against the single 110-grain fragment and the 12.7-mm API in that the peak pressure was limited to less than 4 psig. Partial success was achieved against the 23-mm HEI in that the peak pressure was limited to 40 psig (unsuppressed peak pressures average about 55 psig). These results (given in Table 10) clearly indicate that the SCS system partially suppresses the explosion, but suggested that the optimum distribution of agent is not being achieved sufficiently rapidly after ignition.

Table 10. Comparison of Peak Pressures in a Flammable Ullage With and Without SCS

Threat	Without suppressors (psig)	With suppressors (psig)
Single 110 grain fragment	80	4
12.7 mm API	65	5
23 mm HEI	55	40

SCSs filled with pentane to provide a 47% concentration (approximately 54% mass fraction) suppressed explosions in a 30 cubic-foot (ft^3) volatile ullage simulator initiated by both a single 110-grain fragment and a 12.7-mm API. Partial suppression only was realized against the 23-mm HEI. [13]

In other SCS testing, the device worked successfully with Halon 1301 in a small fuel tank. However in a larger tank, the required number of bottles increased. It is imperative to expel the agent at an effective concentration. It is difficult to get agent flow at a certain velocity. [20]

Weight And Cost Implications

The system weights were provided in Table 11. The system weights could be reduced if the system can be made efficient by localizing the protected area.

Table 11. Estimated Systems Weight and Procurement Costs

	Tank Vol. (US Gal)	Sensors qty/wt (#/lb)	Suppressor qty/wt (#/lb)	Controller weight (lb)	Misc weight (lb)	Total System weight (lb)	Est Costs ($) *
Large Transport							
+ Canister Suppressor	25000	50/20.0	400/280.0	4	20	324	$303,000
Hemi Suppressor		50/20.0	125/312.5	4	62.5	399	$150,500
Medium Transport							
+ Canister Suppressor	10000	35/14.0	250/175.0	4	15	208	$196,500
Hemi Suppressor		35/14.0	85/212.5	4	42.5	273	$106,000
Small Transport							
+ Canister Suppressor	2000	20/8.0	100/70.0	4	10	92	$90,000
Hemi Suppressor		20/8.0	40/100.0	4	20	132	$58,000
747 CWT							
+ Canister Suppressor	17000	40/16.0	378/264.6	4	18	302.6	$278,800
Hemi Suppressor		40/16.0	40/100.0	4	20	140	$76,000

+ Canister is an out-of-production design
* Ball-park costs based on units identified in study and current production costs.
No estimates made for installation on new acft or as a retrofit on existing acft.

The installation labor costs per aircraft are estimated to range from $7,000 to $17,000 if accomplished during scheduled maintenance while fuel tanks are open and are based on a labor rate of $45 / m-hr. There are no known system operational costs. Unscheduled maintenance costs, comprised of costs of delays, cancellations, out-of-service time, and maintenance man-hours and materials, have not been determined due to lack of reliability data. Detonator replacement is estimated to be required at 10 year intervals and would occur at major maintenance cycles; however, the material cost is not available.

Effects On Other Aircraft Parameters

Ullage explosion protection systems have been installed in British military aircraft used in service. No safety problems are known.

It is anticipated that all the sensors and most or all of the currently available hemispherical type suppressors could be located in the ullage. Therefore, no fuel volume reduction would occur and no increase in landings due to range reduction or additional fuel consumption would be expected.

Inadvertent system operation has occurred with early type sensors. This is not expected with the later technology sensors presently being used. The observance of proper in-tank maintenance procedures is necessary with any such systems and must include system disarming prior to tank entry for maintenance.

To avoid any hazard related to tank overpressure associated with the discharge of the system, it is designed to sense fuel level and discharge the amount of suppressant required by the ullage volume present. To avoid or minimize the addition of wiring within the tank, the design can provide for sensors mounted against the inside surface of outside tank walls with wiring outside the tank.

For any suppressors that can not be mounted on outside tank walls, wiring for suppressor initiation at momentary five amps per suppressor, must be housed in conduits inside the tank.

Current Status

A lot of IR sensor development has occurred since the original systems were installed. The status of present-day IR sensor technology allows for the successful recognition of and response to, hydrocarbon fires and the exclusion of response to specific anticipated false light sources. The response time is two to three milliseconds and can be made quicker. Sensors would be located outside the tank, with optical viewing ports through the tank walls or flange mounted on the inside tank wall with wires passing directly through the wall. The number of sensors will vary with the size of the tank. [10]

3.2.1.4 Solid Propellant Gas Generators

The use of the solid propellant concept for fuel tank/cell explosion protection for aircraft is relatively new. The concept was investigated for use in portable extinguishers in the late 1950s and for use on engine nacelles in the early 1960s. [21]

Description/Types

Primex Aerospace Company produces various fire suppression and explosion protection technologies that are installed on various military aircraft. They have developed a line of solid propellant gas generators, based on the automotive air bag industry and extending into dry-bay explosion suppression. These systems produce gaseous carbon dioxide, nitrogen and water and can be used directly as a suppressant. This generates a large volume of gas in milliseconds from an electrically initiated, exothermic reaction releasing carbon dioxide, nitrogen, water and trace compounds. Recent versions of these systems were developed around the military's need for aircraft protection against the external, incendiary projectile threat.

Capabilities/Limitations

Company and military tests at China Lake have shown successful ullage protection with response times quick enough to suppress an ullage explosion. Though immersed applications still need to be evaluated and qualified, the technology appears to have a lower sensitivity to variations in ullage volume than a typical halon suppressant release.

The inert gas generation technology has been successfully shown in live fire testing to protect a fuel tank from catastrophic overpressure resulting from API threats, but was to slow to protect a fuel tank against a 23mm HEI. However, the initiation of the gas generators was triggered by the test apparatus or personnel and was not initiated by a reactive sensing device that would be required for explosion suppression systems on aircraft. There is sensing technology available which could trigger the gas generation technology fast enough to suppress an ullage explosion, but this has not been demonstrated. Sensor initiated gas generation systems have demonstrated compliance for aircraft dry bay fire/explosion protection on the V-22 and F/A-18E/F aircraft.

The advantages to inert gas generation technology for ullage protection are as follows:

- Quickly disperses noncorrosive inerting agents without pressurized containers
- Long shelf life (20 years),
- Low maintenance,
- No freezing point depression issues,
- Canisters are not powered except for activation,
- Canisters can be installed in tank where required,
- Can be selectively discharged by a remote controller, and
- Gas is radially discharged resulting in good suppressant dispersion and creates no reaction loads on the aircraft structure.

The disadvantages of inert gas generation technology for ullage protection are as follows:

- High temperatures of discharge gases,
- Controller must know ullage volume and fuel level (FQIS) to ensure tank is not over-pressurized from variable ullage volumes and to ensure canister is not activated under the fuel level (hydraulic ram effect may rupture tank),
- Canister wiring must be routed in tank,
- Volumes larger than 120 cubic feet have not been tested, and
- Single shot canisters require tank entry after discharge and containers are not re-usable.

Another configuration that Primex has developed is a hybrid system where a liquid suppressant is discharged by the gas generator. The expanding gases from the gas generator expel a liquid suppression agent. This has been successfully tested in live fire testing, but has not been demonstrated for fuel tank explosions. The advantages are as follows:

- Long shelf life,
- Low maintenance,
- Usable with any low pressure suppressant,

- No high pressure discharge into ullage,
- Low propellant weigh requirement,
- Ullage volume input to controller desired but not required,
- Canisters are not powered except for activation,
- Can be BITE checked,
- Controllers can selectively discharge canisters, and
- Faster discharge rates than nitrogen charged systems.

The disadvantages of the gas generator-hybrid system are:

- Suitable low pressure suppressant needed,
- Water has been demonstrated effective but has freezing point issues,
- Canister triggering wiring and squibs-initiators must be located in tank,
- Single shot canisters, and
- Requires tank entry to replace after discharge.

The gas generator technology has demonstrated its effectiveness in suppressing fuel tank explosions for military threats up to API projectiles. However, the gas generation technology was not tested with a reactive sensor and has not demonstrated system (sensors and gas generators) effectiveness for an installed aircraft application. There are extremely fast sensors that have been demonstrated effective with other explosion suppression technology in fuel tanks. Therefore, it is likely that the gas generation technology could be effective in suppressing fuel tank explosions. Gas generation-hybrid technology has been shown effective in dry bay applications. However, it has not been shown effective in fuel tank applications.

Weight And Cost Implications

Weight estimates for commercial aircraft utilizing a gas generation technology are given in Table 12 and are for the total tank volume, main and center wing tank (CWT). The bizjet tank volume is shown as 2,000 gallons, but the standard volume is 1,200 gallons. The weights are quite low for all models compared to other methods such as foam and nitrogen inerting. Any aircraft structural changes are not shown but would be minor.

The canisters are one to two inches in diameter and up to one foot long and would occupy a minimal tank volume. The controller located outside of the tank would occupy a small volume and would require no modifications to the airplane to install. The only range impact would be carrying the additional weight shown in Table 12.

Table 12. Estimated Gas Generation and Hybrid Systems Weight and Procurement Costs

	Tank Vol (US Gal)	Sensors qty/wt (#/lb)	Suppressors qty/wt (#/lb)	Controller weight (#)	Misc Weight (lb)	Tot System Wt (lb)	Est. Tot System Cost ($)*
Large Transport							
Active	54,000	30 / 15.0	58 / 290	12.0	40.0	360	$163,500
Hybrid		30 / 15.0	29 / 145	8.0	30.0	200	$141,750
Medium Transport							
Active	24,000	15 / 7.5	26 / 130	8.0	15.0	160	$92,000
Hybrid		15 / 7.5	13 / 65	5.5	10.0	90	$82,250
Business Jet							
Active	2,000	4 / 2.0	4 / 10	3.0	1.0	20	$29,000
Hybrid		4 / 2.0	4 / 10	3.0	1.0	15	$29,000

* Cost estimates based on units identified in study and current production costs
No estimates made for installation on new aircraft or as a retrofit on existing aircraft.

Based on:
Suppressor unit weight = 5.0 lbs each (1000 gram agent)
Sensor weight = 0.5 lb each
Wiring weight = 0.012 lb/ft
Large Transport = 35 ft per component
Medium Transport = 25 ft per component
Business Jet = 10 ft per component

Only the cost of procurement has been evaluated. Since the complete system (sensor and gas generators) has not been demonstrated effective in suppressing fuel tank explosions, a complete cost analysis was not performed.

Effects On Other Aircraft Parameters

If the system were activated with personnel in the tanks, this could result in serious injury. Therefore, the system would have to be deactivated prior to any entry into the fuel tank.

Putting pyrotechnic devices (squib or pyrotechnic initiators) into the tank may present a risk to the aircraft. A full safety analysis would be required to determine the resulting level of safety for the system. Presumably, the fact that an explosion suppressant would be released if the squib was activated would ensure any ensuing explosion would be suppressed.

No other equipment hazards or effects have been identified.

Current Status

Development testing is still necessary to characterize a gas generator system that is compatible with today's aircraft and their requirements.

Putting additional wiring and squib initiators in the fuel tanks presents a new set of safety concerns that need to be addressed. A complete new certification program would be required, considering failure modes and effects analysis. Full-scale testing and flight testing would be required for certification.

This system could require: testing for material compatibility, fuel solubility, gas generator inerting capacity, and toxicity; servicing; safety; fire and explosion detection; analysis of impacts on engine components and operation; flight certification; manufacturing; handling; logistics; and redesign of an entire system. [10]

3.2.1.5 Nitrogen-Inflated Ballistic Bladder System (NIBBS)

The Nitrogen-Inflated Ballistic Bladder System (NIBBS) is a device for achieving a number of fuel system vulnerability improvements with one system. It is, in the developers' words, "a single system capable of eliminating all of the fuel problems currently requiring multiple mitigation systems. The NIBB inherently self-seals instantly (eliminating dry bay fires in adjacent spaces and stopping fuel depletion), attenuates hydrodynamic ram pressures, eliminates ullage explosions, prevents dry bay fires, and eliminates engine air-intake fuel ingestion".

The McDonnell Douglas Corporation originally conceived NIBBS as a hydraulic ram attenuation device. Naval Air Weapons Center (NAWC), China Lake, California, tested it with considerable success. Subsequently, the Boeing Company, Seattle, Washington, modified the design for ullage protection.

Description/Types

The system consists of self-sealing inflatable bladders on the fuel tank walls. As the fuel is used, the bladders inflate with nitrogen, thus, eliminating the ullage space and producing a protective, inerted air gap between the fuel and the adjacent dry bay. The bladders are semi-permeable, so as they reach the limit of their distension, the nitrogen flows into the growing ullage space, providing inerting to prevent an explosion.

Capabilities/Limitations

The system is in development and has been tested against API and HEI projectiles.

Weight And Cost Implications

There are some weight penalties which are undefined at this time.

Effects On Other Aircraft Parameters

There are some maintainability penalties, but the fuel penalties are very small (limited to the thickness of the uninflated bladder). This is probably the most advanced and complete ullage explosion hazard system. [2]

Current Status

The Boeing Company, Military Aircraft Division in Seattle, Washington, was contacted to provide this information. However, no information was provided in time for incorporation into this report.

3.2.1.6 Pacific Scientific

Description/Types

Pacific Scientific produces a line of fire extinguishing products, specifically for dry bays and classically defined fire zones, and a line of fire suppressors specifically designed to protect the occupied compartments of military armored ground vehicles against an external projectile threat and secondary, internal explosions. The occupied compartment fire suppression system utilizes a three-frequency optical sensor, a non-microprocessor controller and solenoid opened suppressant bottles, specifically tailored to maintain a survivable atmosphere after discharge. The military ground vehicle fire suppressions systems must suppress a fire/explosion in occupied vehicles such as tanks and armored personnel carriers. The overpressure heat, oxygen concentration, hydrocarbon combustion by-products, and the toxicity of the agent must be survivable and meet military specifications. The sensor is a discriminating, three-frequency optical sensor that has good false alarm immunity and will not fire the suppressant for a long list of false light sources. The halon bottles are solenoid activated, not squib activated.

For the F-22 dry bay protection scheme, Pacific Scientific designed stand-alone sensor-bottle combinations that can react more quickly than their standard extinguishing technology. This system incorporates multiple 'bottles', using Halon 1301, to provide appropriate coverage. The F-22 dry bay protection system has sensors on each bottle, and BITE check capability.

Capabilities/Limitations

The technology has not been demonstrated to protect against explosions in fuel tanks.

Weight And Cost Implications

No weight estimates were developed, since the applicability of this technology is not known for explosion suppression in fuel tanks. No detailed design was performed, and no weight data was submitted. Furthermore, no sizing estimates were developed.

Since the technology has not been demonstrated to protect against explosions in fuel tanks and a system design was not developed, an exhausting cost benefit was not performed. The estimated costs shown in Table 13 were provided by Pacific Scientific.

Table 13. Cost Impact

DESCRIPTION	QTY	$ EACH	$ TOTAL
Optical Sensor	8	900.00	7,200.00
Amplifier	1	5,000.00	5,000.00
Extinguisher	8	1,600.00	12,800.00
Control Unit	1	5,000.00	5,000.00
Cable Harness	1 set	15,000.00	15,000.00
Brackets/Misc. fixing devices	1 set	10,000.00	10,000.00
TOTAL			$45,000

Effects On Other Aircraft Parameters

Pacific Scientific does not manufacture and have not tested explosion suppression systems for fuel tanks. Other Pacific Scientific fire suppression systems have been qualified in military applications. However, the effectiveness of this technology for fire suppression in fuel tanks has not been demonstrated or determined. If this could be demonstrated, then the safety of discharging into a variable ullage volume and possible discharges under the fuel would have to be demonstrated. Possible wing overpressurization could result if the system designed for an empty tank discharges into a full tank. Also, the hydraulic ram effect of discharging the agent under the fuel could cause the tank to rupture.

Since the inadvertent firing of the agent when personnel are in the tank is a potential threat, the system would be de-energized before entering the tank.

Possible tank overpressure could result from the discharge of agent sized for an empty tank when the tank is full. Also the hydraulic ram effect if the agent is discharged under the fuel could rupture the tank.

Current Status

None of the Pacific Scientific components or systems has been tested in a wet-bay. A significant amount of additional development and testing to provide adequate protection in this environment is needed. For a complex aircraft fuel system, additional development for alternate, more suitable suppressants, and microprocessor controllers to deal with multiple bottle arrays and variations in ullage volume must be conducted to minimize any overpressure hazard.

Pacific Scientific does not manufacture and have not tested explosion suppression systems for fuel tanks, only for applications in dry bay and occupied areas. Significant development would be required to adapt their current technologies to fuel tank applications. It is not known how much signal attenuation and signature shift would occur with a fuel film over the sensors and how their discharge bottles would react in a submerged environment. Further development would be required to account for variable ullage and discharge pressure by using microprocessor controls and multiple bottle arrays.

The effectiveness of this technology has not been demonstrated in preventing over-pressures in fuel tanks, only in military aircraft dry bays. A complete testing program will have to be performed to demonstrate proof of concept and design before any certification testing can be performed. Prevention of tank overpressure in a variable ullage volume and the effects of discharging the agent under the fuel would have to be demonstrated. [10]

3.2.1.7 Bureau Of Mines Explosion Suppression Systems

The Government requested that SURVIAC investigate previous explosion suppression research performed by the Bureau of Mines.

Over 500 major dust or gas explosions have occurred in coal mines during the past 100 years in the United States. The Bureau of Mines has been studying dust explosions in both laboratory and full-scale mine tests since 1910. [22]

Description/Types

The main protective measure presently used in U.S. mines to prevent explosions is generalized rock dusting. Rock dust (for example, limestone, dolomite, or shale) is applied throughout the mine to inert the coal dust. The technique may not be totally effective in mine areas where fresh dust is being produced at a rapid rate. Therefore, other means of protection are required to supplement generalized rock dusting.

Additional protective measures have been aimed at preventing ignition or rapidly suppressing flames after they have started. Suppression of coal dust explosions using barriers (both triggered and passive) has been investigated by the U.S. Bureau of Mines. Explosion suppression barriers are devices that contain fire extinguishants that are activated to disperse at some critical point during the propagation of an explosion in order to suppress it. Barriers have been experimentally demonstrated, and some are used in mines in Europe for protection against coal dust explosion. Triggered barriers typically consist of a flame sensor, disperser, and extinguishing agent. The flame sensor activates the disperser, which rapidly releases the agent stored under pressure. [23]

Dry powders have been demonstrated to be extremely effective explosion suppressants in underground mine applications where speed is also important. Dry powder acts to halt propagation by attracting free radicals from the combustion components, thus, preventing the coal dust (fuel)/air (oxygen) interaction. This is a rapid, effective means of explosion suppression. [11] The inhibitors consisted of rock dust ($CaCO_3$), BCD ($NaCl$), Super K (KCl), Purple-K ($KHCO_3$), BCS ($NaHCO_3$), ABC ($NH_4H_2PO_4$), water, hybrids of water plus Halon 1301 (CF_3Br) or low-expansion foam plus Halon 1301, and pure Halon 1301. [24]

The U.S. Bureau of Mines Pittsburgh Research Center (PRC) found that by mixing dry powder with a chlorofluorocarbon (CFC) propellant such as a halon or Freon, delivery speed of fine powders can be increased enough to suppress methane explosions before they trigger a coal dust explosion in underground mines. [11]

Capabilities/Limitations

One study designed tests to measure flammability limits of combustible dusts with and without added inhibitor dusts. They used passive barriers to suppress the coal dust explosion propagation. They also use limestone rock dust to inert coal dust (70 percent limestone dust in the mixture). They also used inhibitor dusts which included extinguishant powders, such as ABC (ammonium phosphate), BCD (NaCl), Super K (KCl), and Purple K ($KHCO_3$) in addition to the limestone (calcium carbonate ($CaCO_3$)). [22]

Another study tested water and ABC powder (ammonium phosphate). Triggered barrier systems for protection against incipient gas explosions were tested in a simulated longwall panel. Results show that ABC powder was much more effective in suppressing the developing explosion than equal amounts of water released from the same pressurized reservoir. Although water was effective in stopping fully developed dust explosions, it had little effect against an explosion during its incipient stage. It was established that without the barriers, the methane explosion would propagate and result in the maximum pressure rise of 1.38 bar (138 kPa) at the mine face. In the tests interpreted as "suppressed," the flame did not propagate more than 15 m beyond the ignition source and the maximum face pressure rise was less than 0.57 bar (57 kPa). Through effective powder dispersion, such as from a pressurized triggered reservoir, ABC powder is a viable explosion-suppressing agent. [24]

A third study discussed hybrids that had been previously shown to be excellent inhibitors against gas flames. Particle diameter of the rock dust was approximately equivalent to that of the coal dust. The other dust inhibitors were commercial-grade fire extinguishant materials containing fluidizing agents and having particle diameters also similar to those of coal dust. Efficiencies of the extinguishing agents were assessed by the quantity of agent required when premixed with the coal dust to prohibit flame or explosion propagation and by the quantity of agent dispersed from a triggered barrier necessary to stop a propagating coal dust explosion. Two triggered barrier systems were used. One uses a Cardox cylinder, the other a Fenwal vessel. The Cardox cylinder develops a high-pressure gas (about 1,000 atm) to eject the suppressant (about 10 kg); whereas in the Fenwal vessel, nitrogen gas or halon at a pressure of about 15 atm drives the suppressant (13 kg). The barrier consisted of two or more Cardox or Fenwal units containing 12 to 60 kg of extinguishant, positioned approximately 100 m from the mine face. An infrared flame sensor located about 25 m upstream of the barrier was used to trigger the barrier. The suppressant effectiveness was in the following order: $NH_4H_2PO_4$, Halon 1301, aqueous foam or water combined with Halon 1301, water, NaCl, KCl, $NaHCO_3$ (significantly less effective than KCl), $CaCO_3$, and $KHCO_3$. [24]

The limiting factor with powders is speed of delivery. As powder effectiveness is governed by total exposed surface area of the power per unit weight, finer powders equate to increased effectiveness. However, in fuel tanks, the powder may have to travel some distance to reach the explosion flame front before it propagates. Elementary ballistics show that speed of delivery decreases with decreasing powder grain size due to velocity losses. Therefore, larger powder grains would be required to extinguish the ullage explosion before lethal overpressures are reached. These larger powder grain sizes would decrease the effectiveness of the powder in extinguishing the combustion once it got there. [11]

Weight And Cost Implications

No data were available at the time of this report.

Effects On Other Aircraft Parameters

A significant drawback to dry powders is engine and fuel system damage, including corrosion and clogging of fuel system components as well as deposition and hot-metal corrosion in the hot section of the engine. These could occur if, after explosion-triggered or accidental discharge, particulate contaminated fuel from the tank is transferred downstream. Because the ability of powders to suppress explosions is related to total surface area per unit weight, powders have been most effective at seven to ten micron particle sizes. This would pass through any filters currently used in aircraft fuel systems. Research indicates, however, that the powder would agglomerate, forming a sludge in the bottom of the fuel tank. However, it is probable that the agglomerated clumps of powder would be trapped in the fuel system filters. If the filters are plugged by the clumps, and the system reverts to bypassing the fuel around the filter, there is a possibility of clogging the engine fuel controls and combustor nozzles. During experimental dumping of large quantities of coarse Arizona road dust in the fuel supply of a General Electric F100-GE-100 engine, the engine tolerated as much dirt as there would be powder used in this system. However, further testing with CFC-propelled dry powders would be appropriate, and full system flushing after discharge would be required. [11]

Current Status

The chemical process industry utilizes the same agents that are used in coal mine explosion suppression. There is a heavy reliance on the Bureau of Mine data in the military as well as in industry. [25]

3.2.1.8 Gas Research Institute Explosion Suppression Information

Department of Transportation (DOT) "20 Day" Reports indicate that fire-related incidents during repair of gas distribution pipes in excavations resulted in a yearly average of 1.5 deaths and 20 injuries requiring hospitalization in the U.S. during an 11-year period.

Description/Types

Small, stationary, dry chemical ($KHCO_3$) systems with automatic flame, automatic heat or visual detection offer the means for rapid suppression with less interference with escape.

Capabilities And Limitations

The effectiveness of dilution or removal of escaping gas is not established because accident reports do not quantify the leak rate. [26]

Weight And Cost Implications

No data were available at the time of this report.

Effects On Other Aircraft Parameters

No data were available at the time of this report.

Current Status

No data were available at the time of this report.

3.2.1.9 Zvezda Halon 2402 Reactive Explosion Suppression System

Description/Types

Zvezda (a Russian survivability company) utilized a Halon 2402 system as a helicopter fuel tank protection. It has a hemispherical head that explodes upon detection of an incendiary by a photo detector. Halon 2402 was expelled as a liquid and therefore did not present a potential for overpressurizing the tank. Some of the current halon alternatives have high boiling points (like Halon 2402). This fact may make their utilization more appealing.

Capabilities And Limitations

No data were available at the time of this report.

Weight And Cost Implications

No data were available at the time of this report.

Effects On Other Aircraft Parameters

No data were available at the time of this report.

Current Status

No data were available at the time of this report.

3.2.2 Detection Systems

An integral part to the reactive system is the detection system. This section will discuss different types of detectors, their capabilities and limitations, their weight and cost implications, their effects on other aircraft parameters, and the state-of-the-art.

3.2.2.1 Description/Types

Detection systems can be classified as thermal, optical detection types or pressure activated devices.

Thermal Detectors

Thermal Detectors are either spot type or continuous. The spot type devices are used in situations where they are expected to sense a localized heat source, such as in an engine nacelle. The only spot devices approved for aircraft use are bimetalic switches. A typical thermal spot detector consists of a sealed tube in which two low-expansion struts carry two electrical contacts. When the tube expands longitudinally due to heat, the struts are lengthened, straightening out the bowed tube bringing the contacts together. When the tube cools, the struts resume their original bowed position with contacts apart. Because it is a mechanical device, it must be tested periodically by a simple continuity test.

Continuous detectors are able to provide a broader coverage than what is available from spot detectors. The continuous fire detector is a long capillary tube filled with a temperature sensitive material capable of sensing a temperature change anywhere along its length. Most of these continuous detectors are electrical in nature, so electrical connectors are provided at each end of the capillary, making a "sensing element," as it is generally called. The sensing elements can be connected to make a detector that can then be strung either as a loop or as a long string. Loops have the capability to be severed anywhere along their path and still sense temperature changes, since both ends are connected to the control. Continuous fuel fire detectors can be a thermistor type, a eutectic salt type, a pneumatic type, or a capacitance type. [1]

The thermistor types have been used on the F-15 and DC-10 engine and auxiliary power overheat and fire detection systems. Eutectic salt continuous element detectors have been used on the F-15, F-111 and F-4 bleed air overheat detection systems. The pneumatic types have replaced the thermistor type on military aircraft because of false fire warnings. [27]

A comparison of the continuous element systems is shown in Table 14.

Table 14. Comparison of Continuous Element Type Detectors

Type Detector System	MFG.	Method of Detecting		Detector Sensitivity		Detector Set – Point ΔT	Effect of Element Damage			Element Extension
		Overheat	Fire	Effect of Element Length	Effect of Ambient Temperature		Crushing	Chaffing	Severance	
Thermistor	1 Edison 2 Graviner 3 Kidde	Log mean average of resistance	Log mean average of resistance	Increases with length	Increases with temperature, and has extreme sensitivity to hot spots	200° to 400°F depending on ambient environment & element length	No change if shorting does not occur	No change if shorting does not occur	Sensitivity decreases due to shorter length of element remaining, provided shorting does not occur	Individual elements can be connected in series
Eutectic Salt	Fenwal	Discrete	Discrete	No change	Insensitive until set-point temperature is reached	50° to 100°F	No change if shorting does not occur	No change if shorting does not occur and moisture does not enter	No change if shorting does not occur and moisture does not enter	Individual elements (15 feet max.) can be connected in series
Pneumatic	Systron-Donner	Semi-discrete arithmetic averaging of pressure	Log mean of pressure	Decreases with length	Increases with temperature and is insensitive to hot-spots	150°F in well ventilated areas & 250°F in poorly ventilated areas	No change	May still function but only under severe fire condition	May still function but only under severe fire condition	Cannot connect individual elements together. Maximum element length 40 feet.

Optical Detectors

Optical Detectors are either nondiscriminating or discriminating. The nondiscriminating types scan a wide portion of the emission spectra without identifying any particular portion of the spectra. An example of a discriminating detector is an HTL sensor that employs three detectors responsive to radiation in narrow wavelength bands in the infrared (IR) and visible regions of the optical spectrum. Two silicon photodiodes, on responsive to infrared radiation centered at 0.9 micron and the second responsive to visible radiation at 0.6 micron, are employed with a high-speed thermopile responsive to infrared radiation at 4.4 microns. The wavelengths of 0.6 and 0.9 microns are associated with the radiation produced by an exploding HEI projectile while the 4.4 micron band corresponds to a peak radiation emission of a hydrocarbon fuel fire. If the signal strengths meet predetermined levels, then the detector will signal the suppressor system to fire. [1]

Optical detectors have been widely applied in combat vehicles and are well-accepted throughout industry. They are selected for their sensitivity to specific wavelength bands and their responsiveness. Incident radiation optical sensors are of four basic types: photoemissive, photoconductive, photovoltaic, or photodiode. One major advantage of optical fire detectors is their ability to detect, i.e., sense signatures and then follow a logic sequence to discriminate between fire and extraneous phenomena significantly faster than alternative detectors. However, optical detectors have a tendency for false alarms.

All types of optical detectors currently use electromagnetic radiation (emr) sensors, i.e., ultraviolet (UV), visible light, and IR, use the same basic physical phenomena to function. The materials used in these sensors differ because of the different reactions of these materials to emr of different wavelengths.

UV radiation sensors function similarly to visible light and IR sensors. UV sensors differ primarily in the materials used; the materials are sensitive to UV radiation rather than IR or visible light radiation. UV sensors are not often used alone in military equipment; they are sometimes used in conjunction with IR sensors to discriminate better between fire and solar radiation. UV sensors are used primarily in industrial applications. Typical response to an intense UV source is less than 25 ms. Systems are available for applications in which response times of less than 10 ms are needed.

The most commonly used detectors for combat vehicle applications are the IR detectors. In the past IR detectors have been unsuitable for general applications due to the number of IR radiation sources that can be found in nature and thus create a tremendous false alarm problem. Improvements in the ability to discriminate between radiation from a fire and the radiation from other sources, however, have resulted in the IR detector becoming very reliable. Either an optical sensor or a thermopile detects IR. Optical IR detector systems normally use sensors that have been designed to respond to a specific IR frequency. By adding a second or third sensor element each tuned to a different frequency and/or with a different filter, it is possible to improve the ability of the system to distinguish fire conditions from extraneous blackbody radiation.

Since most non-fire stimuli do not radiate in all of the spectral bands monitored, false alarm susceptibility has been greatly reduced.

A number of reliable, efficient, and quick-responding optical detectors exist for use in suppression systems for combat vehicles. The IR and UV sensors are capable of responding in the few-millisecond range. The IR sensor has the fastest response time of all the sensor types, and its IR sensor response time should be in the 4- to 6-ms range. The necessity to discriminate between emr signatures can increase the response time of this sensing system to a range of 9 to 150 ms with an average somewhat greater than 30 ms. All three types of detectors are susceptible to certain extraneous stimuli; thus they can give false alarms. The IR and combination UV and IR detectors can be designed with built-in tests or to be checked manually. Of the three types of detectors, the combination IR and UV has the lowest false alarm rate. The multiple IR detector also has a low false alarm rate.

The disadvantages of the optical detectors follow:

- Susceptibility of opaquing of their windows by oil, dirt, and other contaminants.
- Restricted fields of view, particularly in crowded compartments.
- Selective absorption of emr by smoke, vapors, and other airborne materials, which reduce radiation intensity.

The number of optical sensors required is governed by the field of view and range of each individual sensor; the space to be monitored, masking of space by objects, and location of extraneous radiation sources within the compartment; needs for redundancy of coverage; and potential sources of obscuring materials within the compartment.

The same factors that govern the number of sensors to be used affect selection of the locations of the sensors. Locations are selected also to minimize cleaning and maintenance efforts, potential ballistic damage, contamination of the windows and/or obscuration, effects of hot spots, and exposure to potential sources of false alarms. [28]

Pressure Activated Devices

Pressure Detection devices date back to the time before more discriminating and responsive detectors were developed. An early attempt to provide fuel tank protection from HEI impacts utilized a pressure switch device mounted on the side of the fuel tank. The pressure switch was connected to a roll-up type bladder that was gas activated by the signal from the pressure switch. The early COBRA detection/suppressions system also utilized a pressure transducer immersed in the fuel tank as the signal device. When the device due to projectile or fragment impact senses a predetermined pressure, the sensor triggers an initiator to activate extinguishers. This system can be used for both dry bay or ullage regions. The reaction time for the system is slower than the optical but on a par with the thermal. The COBRA system was subsequently paired with optical detectors in NAWC tests in the late 1970s. While it would be possible to design a detector system that combined optical with pressure, the need or usefulness of such a combination has not been shown to date. Development of both nondiscriminating IR detectors and discriminating detectors is resulting in response times of one to five milliseconds.

3.2.2.2 Capabilities And Limitations

Optical detectors have problems with false alarms. A reactive system also requires aircraft power in order to operated. The requirement for external power represents an added vulnerability factor over passive protection concepts.

Optical sensors and their electrical wiring are vulnerable to damage caused by ballistic impact and penetration from fragments which could render the system inoperative prior to suppressor activation. The inherently slow response of discriminating sensors makes them more vulnerable to fragment damage than nondiscriminating sensors due to the possibility of fragments cutting wires or striking control boxes before the system completes operation. However, redundancy of components can compensate for this deficiency.

The maximum temperature that the area attains during normal operations also limits the application of optical fire sensors. Currently, infrared sensors are limited to a maximum operating temperature of about 125°C (257°F). At higher temperatures the sensitivity of IR detection elements decreases significantly.

Since most fuel tanks are simple geometric shapes. Therefore, detectors can be placed and sized to provide adequate explosion protection. The detectors should be placed to view the most likely direction of ballistic attack.

3.2.2.3 Weight And Cost Implications

System weight will depend upon the number of detectors and suppressors required for any given aircraft. A variety of newer systems/components are currently available, and they should be lighter as well as more effective.

3.2.2.4 Effects On Other Aircraft Parameters

Any system that is utilized for fire/explosion protection must be evaluated for its effect on maintainability and reliability. Maintainability not only includes the items in the system itself but compatibility with maintenance of other aircraft components. Components that require periodic inspection should not be masked or require the removal of fire/explosion components in order to conduct normal maintenance.

The service life of the fire sensor is unlimited due to the built-in test (BITE) features. So long as the BITE registers positive, the sensor is 100 percent operational.

The maintenance costs associated with routine inspection and testing of the protection system would be minimal, because these functions can be performed during normal preflight and postflight inspections.

Periodic inspection of the sensors is required. The sensors need to be inspected for the presence of contaminants on their detection elements and for inadvertent damage caused during maintenance operations.

Cables would have to be installed to provide power and a means of monitoring the status of the sensors and suppressors. For minimum survivability, these cables should be protected to prevent combat damage.

The protection system either would have to be integrated into existing onboard fire warning indicator systems or new indicators would have to be installed. [1]

Windows on the sensors need cleaning to remove possible film of contaminant from the fuel.

3.2.2.5 Current Status

This section describes some example fire detection systems.

Spectrex Optical Fire Detector

The UV/IR high speed detector (fire detector Model 20/20F) for propellant and ammunition explosion detection with its ultra fast response is designed to meet the two important requirements: fast response time (less than 5 milliseconds) and high reliability (immune to false alarms). Model 20/20F flame detector is the new derivative of Spectrex's well-known armored vehicle explosion suppression system (The SAFE System). Over 20,000 of these flame detectors have been protecting armored vehicles and other military applications with proven performance, durability and reliability, over the past 10 years.

The U.S. Air Force Fire Research Laboratory at Tyndall AFB has tested the ultra high speed detector. It has the following characteristics:

- Less than 5ms response time,
- Highly immune to false alarm,
- Distinguishes fire and vapor explosion from other non threatening radiation sources,
- 90°/ 70° Cone of Vision,
- Designed and built to military specifications,
- Explosion proof, and
- MTBF Minimum 100,000 Hours.

The 20/20F model has a continuously self-adjusting, pre-set detection level. Its level of sensitivity is maintained over a wide temperature range, and is independent of background radiation. The 20/20F flame detector is an industrial version that is housed in an Ex housing and it is produced and tested to the highest standards of performance. The detector is sensitive to radiation in two frequency ranges of the electromagnetic spectrum: the infra red (IR) and the ultra violet (UV). Only simultaneous sensing these two radiation ranges will result in a detector output pulse. [29]

Omniguard Model 750

Omniguard Model 750 by Armtec combines an UV sensor and a thin-film thermopile. The thin-film thermopile, senses the narrow band of the carbon dioxide spike at an approximate wavelength of 4.3 μm, and the UV sensor senses at a wavelength of 0.22 μm which is above that of solar radiation reaching the surface of the earth. The typical overall response time is 150 ms for a saturating signal.

Santa Barbara Research Center Dual Spectrum Infrared Sensors

The Model PM-34 Duel Spectrum Discriminating IR detector monitors radiation in two spectral bands to detect intensity above preestablished levels and uses a third IR sensor to provide other fire signature information. The two spectral bands are ones in which hydrocarbon fires emit radiation but not by most non-fire stimuli. The sensors will respond to an explosive fire in 2 ms. [28]

Det-Tronics Dual Spectrum Infrared Sensors

The Det-Tronics PM-5MP Dual Spectrum IR flame detector is optimized for the rigorous semiconductor fabrication industry. The detector incorporates unique Dual Spectrum infrared sensor technology, which establishes a new standard in flame detection and false alarm immunity. The housing is polypropylene that enables it to be utilized in both solvent or chemical etch wet benches. Its characteristics include: [30]

- Built-in rugged mounting plate,
- Typical alarm response of 1 second, and
- Explosion response capability 25 milliseconds.

The U7698E single frequency IR detector provides reliable fire protection for hydrocarbon fires in areas that can present problems for other types of optical detectors. The U7698E is ideally suited for the protection of high pressure fires due to the high speed detection capability pared with the patented time domain signal analysis program for false alarm rejection. Its characteristics include: [31]

- Ignores false alarm sources such as arc welding, lightning, chopped sunlight and x-rays,
- Calibrated automatic optical integrity check, and
- 30 millisecond high-speed response capability for high pressure fires.

The U7602E UV flame detector combines the time proven Det-Tronics built solar insensitive UV sensor. The advanced arc signal processing technology provides a new level of false alarm immunity with the highest level of versatility and reliability in UV fire detection. Its characteristics include: [32]

- Ultra high-speed capability (10 ms),
- Calibrated automatic optical integrity check, and
- Internal reflection optical integrity provides improved reliability with less maintenance.

HTL Optical Fire Sensor Assembly

The HTL optical fire sensor assembly combines two narrow band optical sensors, one visible and one IR, and a narrow thermopile. It will detect explosions within 2 to 4 ms from receipt of radiation generated by a hydrocarbon explosion. [1]

3.2.3 Active (Pre-Protection) Systems

The active systems discussed in this report include: OBIGGS, Total Atmospheric Liquification of Oxygen and Nitrogen (TALON), carbon dioxide, exhaust gas, fuel fogging, anti-misting fuel, BlazeTech bubbler, air purging, fuel scrubbing, ullage washing, fuel tank ullage sweeping, catalytic combustor, HFC-125, FC-218, CF_3I, and dry powders.

3.2.3.1 Onboard Inert Gas Generator Systems (OBIGGS)

Nitrogen gas has been found to be an effective fire/explosion inhibitor and is very well suited for application to fuel tank systems. [1] OBIGGS is a newer technology in the family of nitrogen inerting systems. OBIGGS has been tested from the early 1970s to the present. [21] Air Force interest in the OBIGGS concept dates back to the 1960s. [33]

Description/Types

OBIGGS processes high pressure engine bleed air and produces an air supply that has had oxygen removed, resulting in a higher percentage of nitrogen referred to as NEA (nitrogen enriched air). The NEA is then either used in an on-demand mode or stored mode, while the waste product is usually vented out of the aircraft. OBIGGS can be used in both modes. For either mode, there now exist two techniques for producing the NEA: the Molecular Sieve (MS) or the Permeable Membrane (PM). Both of these techniques are also known as Air Separation Modules (ASM), which is heart of the system.

The on-demand OBIGGS is designed to have a large ASM capability so it can meet the high flow requirements that would be encountered during descent. This means that the system has to be sized to meet the most stringent demand. The stored system makes use of a high pressure compressor and a storage bottle that can accumulate a sufficient quantity of NEA to meet short-term high flow rate requirements. This approach allows for a lower steady rate of NEA production than is required for the on-demand system.

The MS technique generates the inert gas by means of a pressure swing absorption system that uses a zeolite molecular sieve material through which the supply air passes to produce NEA. Oxygen is preferentially absorbed within the molecular sized pores of the sieve material at high pressures. While one bed is pressurized to produce nitrogen rich gas on the downstream side, the other bed vents its oxygen rich gas overboard as waste. [1] MS systems have been in use since 1975 on various military aircraft. They can operate with source air pressures as low as 20 psig and temperatures between –20°F and +120°F. They are sensitive to liquids, however, and may need to be replaced if wetted. The absorbed oxygen must also be flushed from the sieve at regular intervals. In operation, this means that two molecular sieves must be available or a valve cycles the source air between them to maintain a constant flow of inerting gas. [34]

The PM technique utilizes hollow methyl Pentane fibers, arranged in a cylindrical bundle around a hollow mandrel that distributes high pressure process air into the bundle. In actual operation, process air is distributed lengthwise through the fiber bundle by the perforated mandrel and then flows out radially through the mandrel. Since the oxygen molecules permeate the membrane walls more readily than nitrogen, the gas inside the hollow tube membranes becomes oxygen rich and is discharged as waste. The gas left over is nitrogen rich and becomes the inertant gas. [1] Permeable membrane systems are completely passive. They rely on the polymer membranes to separate nitrogen from air. These systems have been in commercial use since 1975, but have only recently been applied to aircraft. Permeable membranes work best with source air pressures of 60 psig and temperatures near 140°F. A reduction of source air pressure to 30 psig would require approximately three times more membrane material to maintain the same output flow. A reduction to 15 psig would require ten times more material. Thus, the system weight and its impact on the aircraft are sensitive to the source pressure. Permeable membranes are also sensitive to source air flow. More source air is required to provide better purity (lower oxygen concentration). Three times more source air is required to achieve an oxygen concentration of three percent than for an oxygen concentration of nine percent. The impact on aircraft resources can be minimized if a higher oxygen concentration can be permitted. Contaminates that could plug the membrane material would also require more bleed air to get the same effectiveness as an unplugged membrane. [34]

The F-22 uses a permeable membrane system for ullage inerting and the C-17 uses the molecular sieve system.

Figure 14 depicts the C-17 OBIGGS configuration.

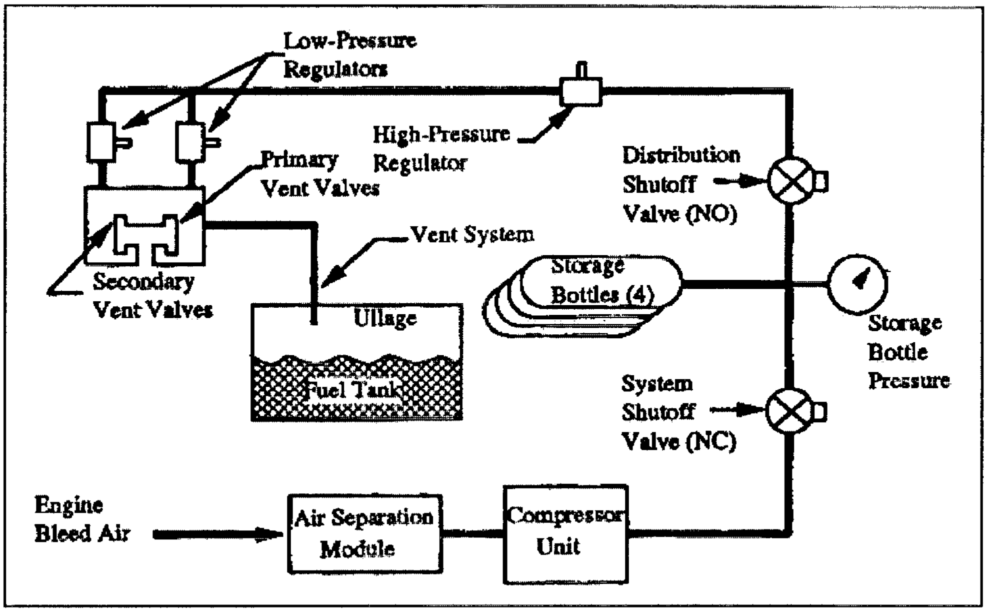


Figure 14. C-17 OBIGGS Configuration

Capabilities And Limitations

A study of the OBIGGS found that either the MS or PM system provides the necessary protection for a fighter type aircraft and could compete with other protective techniques. The application of an OBIGGS system to fighter size aircraft, which would also approximate helicopters, is the most demanding due to the relative size and rapid rates of descent experienced by fighter aircraft.

Permeable membranes and molecular sieves both require a conditioned air source to develop the NEA. Currently, the only air source available in flight is engine bleed air. Present day aircraft are optimized for certain flight regimes, and their systems are highly integrated. Engine bleed air is used by the environmental control system to pressurize the cabin and by the anti-ice system to minimize wing and tail icing. Under some flight conditions, such as takeoff or descent, all of the engine bleed air is used for existing aircraft equipment leaving none available to supply OBIGGS systems. [34]

Weight And Cost Implications

A comparison of some protection system weights is shown in Table 15. While the OBIGGS was not the lightest, it showed weights close to the lightest while offering some other advantages. [1]

Table 15. Protection Systems Comparisons Weight Summary

Assumptions	Stored Gas		Demand		Demand & Emergency Halon		Halon 1301		Ln_2		Foam	
	• Optimal System • Advanced ASM • 0.65 lb/min NEA5 w/boost compressor		• Current System • Advanced ASM • 22 lb/min NEA12		• Current System • Advanced ASM • 15 lb/min NEA12		• Fuel time protection • One mission supply • 20% by volume repress. flow • Fuel absorption 0.6 lb/min		• One time mission supply • Same mass requirement. As OBIGGS stored gas system		• Fine pore • 50% void	
	wt lb	vol ft^3	wt lb	vol ft^3	wt lb	vol ft^3	wt lb	vol ft^3	wt lb	vol ft^3	wt lb	vol ft^3
System Components												
Bleed air supply	5	0.1	90	2	64	1.8	0	0	0	0	0	
ECS (Δ)	7	0.1	55	1.6	41	1.5	0	0	90 (HX)	0	0	
IGG supply air conditioning	6	0.4	35	0.9	21	0.8	2	0.1	0	0	0	
Compressor, motor, intercoolers	83	2.5	0	0	30	0.2	0	0	0	0	0	
Storage bottle & fittings	80	3.7	0	0	20	0.2	42	1.2	54	1.6	0	
IGG	14	0.4	143	3.4	64	1.6	0	0	0	0	0	
Distribution System	38	0.2	42	0.2	39	0.2	17	0.1	12	0.1	0	
NEA, halon, LN2 or foam	25	0	0	0	30	0	107	0	77	0	282	
Retained fuel	0	0	0	0	0	0	0	0	0	0	452	
Total	258	7.4	365	8.1	309	6.3	168	1.4	233	1.7	734	NA

Other points to consider include:

- The stored gas system weighed only 258 lb. compared to the 365 lb. on-demand system. [35]
- A life cycle cost (LCC) comparison was also made for the fighter sized system. The LCC results are in constant 1985 dollars. The stored gas system had the lowest cost. [1]

- The stored gas system (as used on the C-5A) required the Air Force to build cryogenic nitrogen storage sites at key bases around the world. This was not a small investment.
- The projected life cycle costs for the stored gas system were estimated at \$523M compared to \$561M for an on-demand system, \$575M for an LN_2 system, and \$824M for a foam system (78 percent of the cost was in fuel penalties). [35]

Table 16 provides a comparison of the cost of each technology over 10 years. [34]

Table 16. Technology Cost over 10 Years (US Dollars)

On board Liquid Nitrogen for All Tanks	\$35.7B
On board Gaseous Nitrogen for All Tanks	\$33.9B
Air Separator Modules for All Tanks	\$37.3B
Air Separator Modules for the Center Tank	\$32.6B
Ground based Ullage Washing with natural Fuel Cooling for Center Tank	\$4B with gaseous nitrogen \$3B with liquid nitrogen

Effects On Other Aircraft Parameters

While the permeable membrane technology is still in its infancy, it is expected to show continued dramatic improvements because of the highly competitive industrial and commercial gas separation market. From an OBIGGS view, permeable membranes offer the greater potential for future applications. The passive nature of the permeable membranes translates directly into high reliability. At the present time, there are no apparent significant effects of OBIGGS upon flight safety, crashworthiness, maintainability, or repairability.

On-demand systems are more reliable than the stored gas systems and can inert for any mission if designed for maximum descent rate. The on-demand system drawbacks include a large ASM, increased system cycles for multiple descents (higher failure rate), possible sizing effects of environmental control system, and the possibility of NEA demand that exceeds capacity (emergency descents). [35] Operational compromises will almost certainly be required. Many of today's aircraft do not have enough bleed air available to supply these systems. [34]

Whatever the type of inerting that might be used, there are potential hazards to personnel. Gaseous inerting agents present a suffocation hazard, and liquid nitrogen presents the additional hazards of freezing trauma to skin and eyes.

The reliability (maintainability) is a problem. Information presented at the Transport Fuel Flammability Conference, October 7-9, 1997 in Washington DC, showed that the major reliability problems were with the ASM, ASM filter and the compressor. The valves and sensors had a high degree of reliability. Overall system reliability was said to be less than 200 hours between failures and less than 100 hours between maintenance. [34]

Current Status

Technology and design advancements with a reduction in system weight have been achieved allowing full-time protection with an on-demand OBIGGS (which can be installed with minimal overall penalty) to be a viable option. [34]

OBIGGS type inerting systems are currently used on military aircraft, notably the C-17 as well as some fighters (i.e., F-117, F-22) and helicopters (i.e., CH-47 E (special operations), V-22, RAH-66). [34]

Evidence that the inerting system does not leave pockets of high oxygen concentration within the tank should be provided. The effect of oxygen evolving from the fuel during pressure reduction conditions, such as during climb, should be addressed. [35]

3.2.3.2 Total Atmospheric Liquification of Oxygen and Nitrogen (TALON)

The current C-17 fuel tank inerting system utilizes OBIGGS. However, OBIGGS has a high failure rate. The current OBIGGS system design may not meet the new requirements for the C-17 extended range mission. The current liquid oxygen (LOX) system can not support full complement of paratroopers. [37]

NASA (Glenn Research Center – Aviation Systems) in tandem with Boeing, Seattle and the FAA are investigating a technology entitled the TALON (Total Atmospheric Liquification of Oxygen and Nitrogen) system. The U.S. Air Force Research Laboratory (Brooks, AFB) has investigated TALON for its generation of oxygen for MEDIVAC missions. The oxygen is used for the crew and patients and paratroop requirements. Current efforts by the previously mentioned consortium are investigating the use of TALON for its nitrogen generation for fuel tank inerting for both commercial and military requirements. [38]

The objective for this science and technology effort is to develop and demonstrate a system capable of generating, liquefying, and storing nitrogen and oxygen. Other goals of this effort are:

- To provide nitrogen for fuel tank inerting -- oxygen for crew, paratroopers, and patients.
- Use miniature distillation columns for separating engine bleed air.
- Develop a miniaturized cryocooler for liquefaction.
- Flight test a palletized system.

Description/Types

The goal of the TALON system is to develop a single system that self generates, stores, and delivers high purity oxygen (ninety-nine percent) and nitrogen (greater than ninety-six percent). It should also meet all C-17 mission requirements – supports paratroop and aeromedical missions. TALON must resolve current aircraft deficiencies.

Major subsystems of the TALON system include the following:

- Cryocooler - liquefies the gases,
- Nitrogen distillation column - produces nitrogen from engine bleed air,
- Oxygen distillation column - produces oxygen from engine bleed air,
- Inlet air treatment - removes contaminants from the engine bleed air,
- Thermal recovery - recovers cooling capacity of the liquid nitrogen,
- Nitrogen storage and delivery, and
- Oxygen storage and delivery.

Figure 15 shows a simplified schematic of the TALON system.

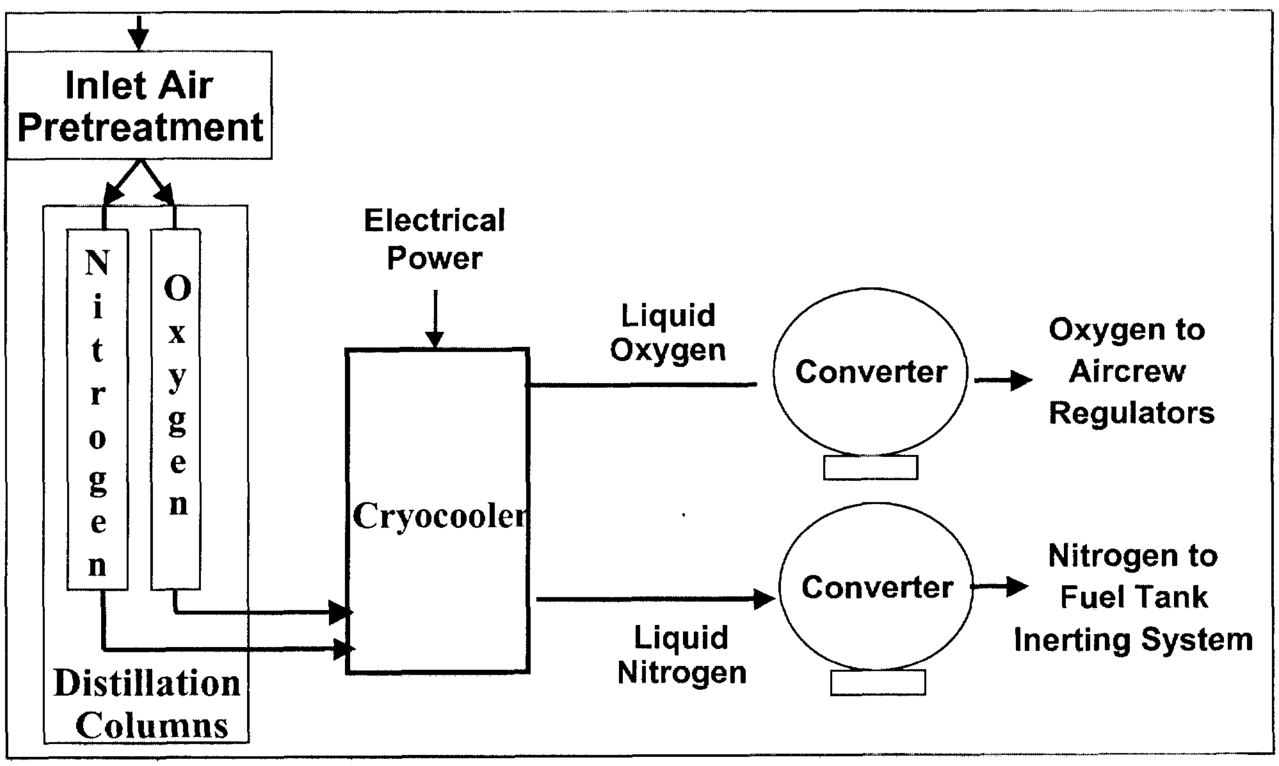


Figure 15. Simplified Schematic of the TALON System

Capabilities And Limitations

Science and technology challenges for TALON include the following:

- Development of lightweight, high-speed turbo-machines (turbo-compressor and turbo-expander) for the cryocooler.
- Development of lightweight, cryogenic heat exchangers.
- Minimize system weight and size.
- Minimize distillation column height.
- Correct for column tilt effects.
- Provide bleed air pretreatment.

Weight And Cost Implications

No data were available at the time of this report.

Effects On Other Aircraft Parameters

No data were available at the time of this report.

Current Status

Table 17 displays the current milestones for the TALON system. [37]

Table 17. TALON Milestones

Milestone	**Estimated Completion**
Preliminary Design (started Sep 99) Aircraft Integration and System Specifications Distillation Subsystem Design Cryocooler System Design Preliminary Design Review	Aug 00
Turbo-machine Development	Aug 01
Detailed Design	Sep 01
Subsystem Fabrication Complete	Aug 02
System Testing Complete	Sep 03

3.2.3.3 Carbon Dioxide

Carbon Dioxide (CO_2) has been a popular fire fighting agent for a number of years. The USAF started looking at using CO_2 for jet aircraft in 1954. [21]

Description/Types

There are three types of carbon dioxide (CO_2) supplies: solid CO_2 kept in cold storage (dry ice), gaseous CO_2 in high-pressure storage bottles, and CO_2 products of combustion. [34]

Capabilities And Limitations

It takes less carbon dioxide than nitrogen to inert a fuel tank. However, combustion inerting systems require that a combustion process occur to develop the CO_2 that is used as the inerting agent. To support the combustion process, a combustion chamber is required which operates at extremely high temperatures and appears to be large in size and shape. The hot CO_2 would be cooled to the required temperature using air-to-air heat exchangers and a source of cool air. These systems must be treated as a fire hazard, which requires they be located in existing fire zones, or that a fire zone be created specially for them. A combustion system would be frugal with aircraft resources requiring little power or bleed air for operation.

Weight And Cost Implications

A cost/benefit/feasibility analysis was not available because of the lack of hardware and test data.

Effects On Other Aircraft Parameters

The dry ice and gaseous CO_2 in bottles require servicing at the military bases. Servicing for the combustion system is dependent on whether fuel or carbon is burned. Carbon combustion would require frequent servicing. Fuel combustion would likely require only periodic maintenance for filter changes, etc.

Current Status

Carbon dioxide dissolves into solution and evolves out of solution more readily than nitrogen. Consequently, fuel boost pump cavitation may occur because of altitude changes, pressure loss in fuel pipes or any other event that causes pressure changes. However, carbon dioxide was not pursued further because it is a greenhouse gas that adversely affects the environment. Its use might be subject to future environmental restrictions or banned completely. Therefore, a more detailed study would be required to determine the feasibility of carbon dioxide as an inerting agent. Combustion systems are currently in the concept or prototype stage of development. [34]

3.2.3.4 Exhaust Gas

Description/Types

The use of exhaust gas was suggested as a means to inert the fuel tanks without adding bulky storage systems to the aircraft.

Capabilities And Limitations

The exhaust gas must be drawn from the turbine section directly, or very close behind it, to avoid the fan bypass air and to achieve lower oxygen concentrations (11 to 15 percent). This section of the engine is typically at 1000°F or higher, and special materials are required to withstand the heat. Any penetration of the turbine case to install a bleed line would weaken the turbine case and increase the chance of engine damage from temperature stresses and vibration. Re-certification would be required to install a bleed line in the turbine case for existing engines and the cost would likely be prohibitive. A failure of the bleed line would create an unacceptable hazard to the aircraft.

Weight And Cost Implications

The collection of engine exhaust gas would require the installation of a bleed air port within the engine's turbine stage(s). Since nearly all engines use fan air to assist in cooling the engine's turbine, the location of the bleed air port would have to be properly located to avoid the fan air. Tapping into an existing engine turbine stage would require extensive and costly engine rework and recertification.

There are contaminates in the exhaust gas that would have to be filtered prior to being introduced into the fuel tank. This would add to the size, cost, weight and maintenance of this method.

A cost/benefit/feasibility study was not performed because of a lack of data.

Effects On Other Aircraft Parameters

Although the autoignition temperature of fuel is 450°F, the exhaust gas must be cooled to 160 °F or less before it can be introduced into the fuel tank to protect components, fuel tank sealants, protective coatings, and fuel bladders. A large precooler would be required to reduce the gas temperature from greater than 1000°F to less than 160°F. Most transport aircraft have their engines mounted on the wings near the fuel tank so the location of a precooler is limited to the engine or engine pylon. On many aircraft, the addition of a larger or an additional precooler is not feasible due to space limitations in the pylon area. Other locations, such as the cargo compartment or the fuselage area could also be difficult due to space limitations and the need to provide outside cooling air to the precooler. This would require a duct and two air scoops on the side of the aircraft that add to the drag.

Another problem is that today's modern high performance aircraft use bulk fuel in the aircraft as heat sink to dissipate the excess heat generated by the hydraulic system and frankly would be hard pressed to accept the addition of heat from exhaust gases.

A high concentration of water vapor in jet engine exhaust that would have to be removed before reaching the fuel tank poses another concern. This is not desirable as water causes tank corrosion, promotes the growth of microbes in the fuel, and possibly would freeze at high altitude and block fuel pump inlets. Aircraft design manufacturers avoid water in fuel tanks and the airlines perform frequent ground checks to make sure water is removed from the tanks before flight. Anything that adds water would require more systems and/or more frequent checking to avoid these problems.

There is also a fuel burn penalty for using exhaust or turbine gas. Turbine gases contribute to the energy needed to drive the engine fan to produce thrust. Exhaust gases expand and help to produce thrust. If some of the gas is diverted for other purposes then there is less thrust. The throttle setting must be increased to make up for the loss of thrust so more fuel is consumed. The estimated fuel penalty would be five to ten percent.

There is a concern about the corrosive effects of the oxides of nitrogen and sulfur in the exhaust gases on the fuel system and tank. Filters would have to be maintained and a monitoring program would be required to avoid adverse affects to the fuel tank. Engine exhaust gas contaminates include high levels of sulfur, nitrogen, oxygen, water, carbon dioxide, hydrocarbons and other engine ingested chemical compounds. These contaminates must be filtered to avoid introducing corrosives into the fuel tanks and the resultant structural integrity inspections that would be required.

Adding to the complexity of installing an exhaust bleed-air port, engine exhaust systems will require conditioning, filtering, overheat protection and a distributing system. For estimating purposes, existing environmental control systems could provide a minimum baseline for determining the size and cooling requirements of an engine exhaust system.

Current Status

It is believed that this technology is not currently viable. However, it may be of value to aircraft designers in the future. [34]

3.2.3.5 Fuel Fogging

Description/Types

The fuel fog system is based on the principle that finely divided liquid fuel (fog) acts as if it were in the vapor state, adding to the natural vapor concentration and thereby driving the tank ullage to the over-rich condition, which prevents ignition.

The system configuration consists of nozzles, filters and the necessary plumbing to flow high-pressure fuel to these nozzles. The fuel fog distribution manifold with fog nozzles must be located to produce uniform fog distribution through the fuel cells under all degrees of ullage and dynamic flight conditions.

Capabilities And Limitations

The fuel fogging technique was found to reduce the threshold for ignition in ullage where a spark source was used. However, when a .30 API ignition was used, fires resulted from every impact. [39] Only drops below 20 micron diameter contributed to an over-rich concentration. Large drops, over 40 micron in diameter rapidly reduce the concentration of the fine mist by coalescence. [36]

System performance is dependent on equipment capable of creating and distributing very small (5 to 50 microns) fuel particles throughout the ullage of the tank. Spraying fuel at high (500 psig) pressure through nozzles designed to produce uniform fog dispersion best does this. With the state-of-the-art equipment, system performance is limited since only partial inerting with jet fuels is possible. There is a depression in the rich flammability limit when a fuel fog is sprayed into the existing ullage of the tank. There is no known way to ensure that the system is always operating at the required performance.

With present state-of-the-art hardware, fuel tank inerting over the entire flammability range of JP-4 has not been realized. The system usage is thus limited to applications where the fuel temperature never gets more than 35°F below its rich limit. Because of this, development effort on this technology has been discontinued. [39]

Additional evaluation of the fuel fog inerting concept was conducted in which the fuel was heated prior to fogging. The flashing of the fuel through the nozzle aperture provides further droplet breakup, resulting in a denser fog. Analysis of these data indicated that a potential inerting capability existed in a two nozzle system, where one nozzle was fed warmer than ambient temperature fuel. Differences in fuel temperature as small as 5°F were tested. All the results of these tests pointed to inerting success when a match-type ignition source was used. Subsequent work with fuel-burner-type nozzles showed that when 0.30 incendiary projectiles were used for the ignition source, fire resulted in the ullage space each time. [2]

Weight And Cost Implications

The fuel fogging technique would require additional plumbing consisting of nozzles, filter and lines. No specific weights or associated costs are available at this time for this technique.

Effects On Other Aircraft Parameters

The fuel fogging technique would increase the maintenance requirements due to the addition of pumps, filter and extra distribution lines.

There is no known way to insure that the system is always operating at required performance. [39]

Current Status

No data were available at the time of this report.

3.2.3.6 Anti-Misting Fuel

Descriptions/Types

During the 1960s, the concept of anti-misting kerosene (AMK) was raised in an effort to reduce the hazard to personnel during post crash fires. Early AMK efforts involved a soap-type chemical additive to the fuel which changed it from a liquid to a semi-solid gel. When subjected to pumping forces, the fuel behaves as a semi-liquid and can be pumped through pressurized lines. [2]

Further testing of anti-misting fuels from the mid to late 1970s examined these additives and their ability to alter the fuel mist or spray during a crash situation by creating large droplets in lieu of the fine mist. Under conditions encountered when a fuel tank ruptures on impact, the fuel exits as droplets instead of a fine mist or spray.

Capabilities And Limitations

Anti-mist additives do not appreciably alter the fuel properties.

In 1973, the Air Force tested AMK to determine if it produced any reduction in the ballistically-induced ullage explosion and found it ineffective in reducing the overpressures with JP-4 fuel, but effective in reducing overpressures in JP-8. [36]

Weight And Cost Implications

No data were available at the time of this report.

Effects On Other Aircraft Parameters

The concept was dropped because of major technical problems associated with filtering out impurities and starting engines.

Current Status

This idea has apparently not been pursued further. [2]

3.2.3.7 BlazeTech Inc.

Descriptions/Types

BlazeTech Inc. is developing an innovative, proprietary method to protect fuel tanks against hydrodynamic ram by producing small gas bubbles (typically nitrogen with a diameter approximately one to three mm and a gas volume fraction of one percent) to attenuate ram pressures. These bubbles drastically alter the wave propagation properties of the liquid fuel which lower the strength of ram pressure pulses. The nitrogen also inerts the ullage space in the tank and eliminates the explosion hazard in the fuel tank. Successful development and implementation of BlazeTech's technology will result in a breakthrough in fuel tank protection that can drastically reduce the overall vulnerability of aircraft in combat and crash situations.

Bubbles can be produced in a number of ways, each of which has its own advantages and disadvantages. For validation and testing purposes, the method used was the easiest conceptually to implement and the results were easiest to interpret. The system, shown in Figure 16, consists of a series of tubes or plates with small orifices used to distribute nitrogen bubbles throughout the fuel tank. Drawing it from the fuel tank ullage recycles the bubble gas. Some nitrogen is also added to the cycle to account for losses through the tank ventilation system. A gas-fuel separator is included in the fuel line to protect the remaining equipment in the fuel system.

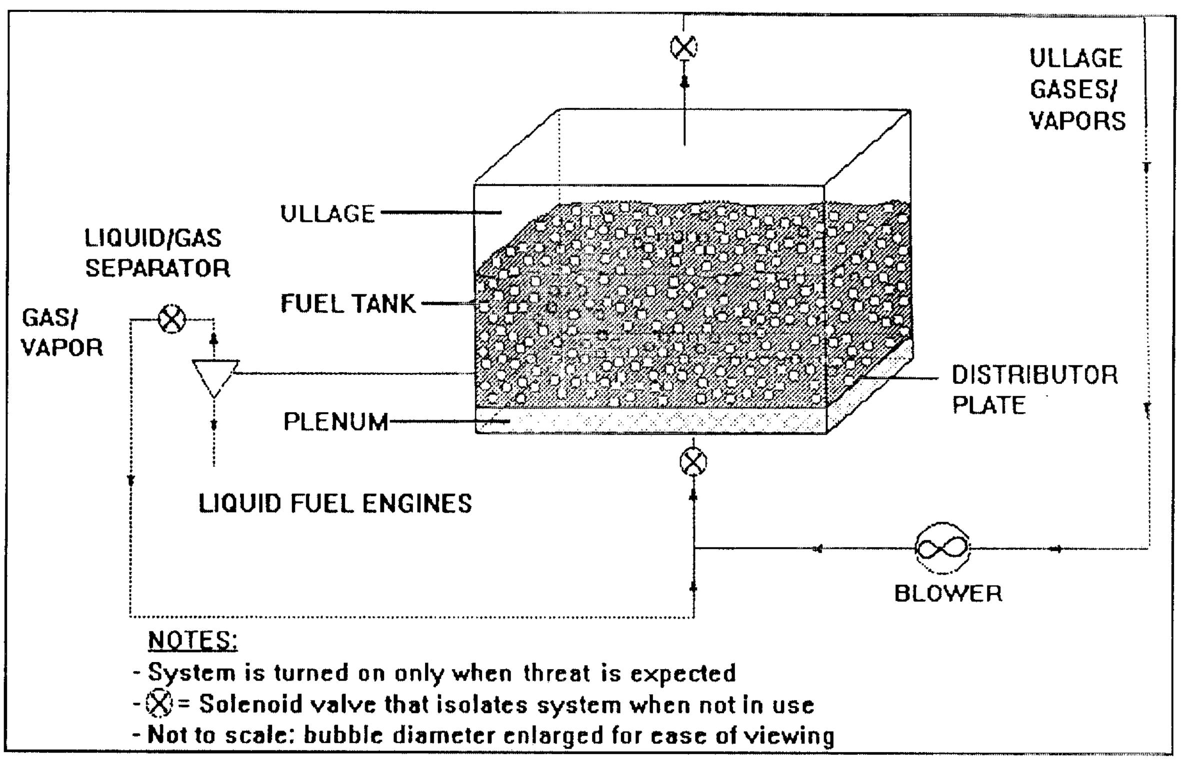


Figure 16. Schematic of Bubble Protection Test System

Capabilities And Limitations

Lab scale testing has produced encouraging results. Using a hammer impact on a piston supporting a column of water, BlazeTech has achieved attenuations of more than 90 percent with void fractions (gas volume fractions) as little as one percent using nitrogen bubbles in water. A similar impact with a small fraction of gas bubbles in the water produced pressures below 100 psig.

Weight And Cost Implications

No data were available at the time of this report.

Effects On Other Aircraft Parameters

No data were available at the time of this report.

Current Status

Current development of the technology for a fighter aircraft application is being supported by the Air Force through a Phase II SBIR project. [40]

3.2.3.8 Air Purging

Descriptions/Types

In a fuel system incorporating fuel management, certain tanks will empty ahead of others. If those tanks that empty prior to entering combat are thoroughly purged of fuel vapors, they will no longer represent an explosive hazard. Air is the preferred purging medium because it does not have to be carried in a storage container aboard the aircraft. Ram pressure, due to forward flight, can provide the motive power. Alternately, engine bleed air can be utilized. In either case, a pair of valves at the opposite extremities of the tank, are opened to provide an air purging inlet and overboard exhaust.

Capabilities And Limitations

The principal problem with purging is that a portion of the liquid cannot be transferred out of the tank, i.e., part of the unavailable fuel. If the quantity of fuel or the area over which it is spread is small, the ability of the fuel to cause damage, if hit, is small, and purging may be a good way to inert the majority of the tank. On the other hand, the use of air as the purge gas, while economical, is all that is necessary to continue a fire, once started.

Weight And Cost Implications

No data were available at the time of this report.

Effects On Other Aircraft Parameters

If engine bleed air is used, care must be taken to keep the temperatures of the purging gas below the thermal limit of the fuel tank and components. The valve on the supply side will incur a negligible weight penalty, but should incorporate a timer to limit the fuel penalty due to bleed air extraction, which could make the use of bleed air unattractive. Ram air, on the other hand, would require a larger and heavier valve, but can be left open for the remainder of the flight. [39]

Current Status

No data were available at the time of this report.

3.2.3.9 Fuel Scrubbing

Descriptions/Types

Fuel scrubbing uses inert gas to dilute the dissolved air in the fuel. This could be accomplished in the aircraft during refueling, or at the air base storage tanks. The scrubbers would be built in to the refueling system (or put inline between the truck and the aircraft) and mix the inerting gas with the fuel as the tank is filled.

Capabilities And Limitations

During climb, the air in the fuel, which is mostly nitrogen due to the scrubbing, will evolve out of the fuel to the ullage. This inerts the ullage during climb and for the early portion of the cruise flight phase. However, the ullage is not inert during refueling, taxi and takeoff.

Scrubbers require a minimum flow in order to work properly. If the flow from the truck or refinery is too slow, then the inert gas will not be mixed into the fuel, and it will not be inerted. The scrubber also adds some pressure drop to the system so more time would be required to fill the fuel tank(s). The primary disadvantage to fuel scrubbing is that it only works if a fuel tank receives fuel. An empty tank would not be inerted. [34]

Fuel scrubbing only gets rid of the dissolved oxygen in the fuel. Therefore, it must be used in conjunction with an ullage protection system.

Weight And Cost Implications

No data were available at the time of this report.

Effects On Other Aircraft Parameters

No data were available at the time of this report.

Current Status

No data were available at the time of this report.

3.2.3.10 Ullage Washing

Descriptions/Types

Ullage washing uses inert gas to dilute the air above the fuel. To be effective, this can only be accomplished on the aircraft. A truck or cart with inerting gas would be connected to a distribution system in the aircraft to deliver the inerting gas to the fuel tanks. Alternatively, an onboard system could provide the inerting gas to the distribution system.

Capabilities And Limitations

The primary disadvantage to ullage washing is that it requires more nitrogen to inert the fuel tank than fuel scrubbing requires. There is also a potential for fuel tank structural damage if the source of inerting gas is not regulated properly. Ullage washing works well in tanks with little fuel but is ineffective in tanks that are full of fuel. This is because the dissolved oxygen in the fuel evolves out during climb and mixes with the inert gas causing the ullage to exceed a nine percent oxygen concentration. A large amount of fuel also means more oxygen is introduced into the tank as fuel is depleted and raises the oxygen concentration above the inert level. On the other hand, an empty tank will stay inerted until descent when the pressure change causes ambient air to enter the fuel tank. Ullage washing of a tank with a fuel quantity of 25 percent or less using NEA that contains 5 percent oxygen or less will remain inert until descent, provided there is no ventilation of the tank during operation. The combination of ullage washing and the normal drop in fuel temperature during a flight can help to limit a fuel tank's exposure to a flammable, non-inert ullage.

A combination of fuel scrubbing and ullage washing avoids the problem of evolving oxygen for nearly full tanks. The ullage oxygen concentration decreases during climb. However, as the fuel is depleted from the tanks, the oxygen concentration eventually exceeds nine percent because ambient air replaces the depleted fuel.

Ullage washing combined with normal fuel temperature changes did prove effective. A statistical analysis combined fuel temperature and flash point with the ullage oxygen concentration that occurs on typical flights in the body (center wing) tank. This generated a time of exposure to a flammable, non-inert ullage. On average, the aircraft was exposed less than one percent of the time. [34]

Weight And Cost Implications

No data were available at the time of this report.

Effects On Other Aircraft Parameters

Current Status

No data were available at the time of this report.

3.2.3.11 Fuel Tank Ullage Sweeping

Descriptions/Types

A positive ventilation system may be used to "sweep" the ullage of flammable fuel vapor/air mixtures at a rate that keeps the ullage lean in spite of a higher than desirable fuel temperature. This technique essentially keeps the ullage below the lean explosive limit.

Capabilities And Limitations

This ventilation system may be used as needed to satisfy the requirement of the regulation, but should address any negative effects such as sweeping unburned hydrocarbons into the atmosphere. Evidence that the ullage sweeping system does not leave pockets of flammable fuel vapor/air mixtures within the tank should be provided. [36]

Weight And Cost Implications

No data were available at the time of this report.

Effects On Other Aircraft Parameters

No data were available at the time of this report.

Current Status

No data were available at the time of this report.

3.2.3.12 Catalytic Combustor

Descriptions/Types

The catalytic combustor, tested from the late 1960s to the mid-1970s, utilized lower operating temperatures and produced no combustion flame. This technique utilizes nitrogen from the surrounding atmosphere as the principal component of the ballast gas admitted to the tanks. Free oxygen is reduced to safe levels by means of catalyzed reaction with a small fraction of the aircraft fuel. Before the combustion gases are admitted to the fuel tanks, the water content is reduced by condensation and by contact with a desiccant.

Capabilities And Limitations

Successful operation of a flight-configured unit achieved a very high effectiveness over a wide range of operating conditions. Inert oxygen gas concentrations below one percent were repeatedly achieved, with the generation of only a small amount of corrosive reaction products. [36]

Weight And Cost Implications

No data were available at the time of this report.

Effects On Other Aircraft Parameters

No data were available at the time of this report.

Current Status

No data were available at the time of this report.

3.2.3.13 HFC-125 and FC-218

HFC-125 and FC-218 are halon alternatives and were examined in the F-16 Halon Replacement Program and will be discussed together.

Description/Types

HFC-125 was the recommendation of the recent tri-service/FAA, multiyear Halon Replacement Program for Aviation to identify solutions for new platforms. Generic and reconfigurable engine nacelle and dry bay mock ups were used to represent the wide range of aircraft fire zone configurations. Statistical experimental design techniques were used to translate the experiments representing a subset of all the possible combinations of fire zones and scenarios into the determination of the extinguishant with the best fire fighting performance i.e., lowest agent weight required to extinguish the fires. Using this approach, HFC-125 was chosen as the best extinguishant for subsequent development of design criteria by a tri-service representative group. This decision also factored in other data and experimentation on the extinguishants' storage and discharge characteristics, toxicity and materials compatibility traits. Once this decision was made, additional experiments were performed to develop a more precise model, again using statistical experimental design, for HFC-125 that would facilitate the sizing of extinguishing systems using it for various aircraft engine nacelle and dry bay applications. This process has been completed, and the design formulas and criteria have been established. [41]

Another test series demonstrated the inerting capability of Perfluorocarbons against the 23mm HEI threat. FC-218 performed better than Halon 1301 under the same test conditions (100 gallon tank wall simulator and minimum venting). [42]

Capabilities And Limitations

The following results are from the F-16 fuel tank explosion suppression replacement and baseline characterization tests. These tests were conducted to allow development of alternative approaches to the current F-16 Halon 1301 fuel tank inerting system.

Five of the 12 shots using HFC-125 against the 110-grain fragment threat resulted in an explosion. HFC-125 provided ullage protection with greater than seven percent nominal concentration. However, the actual agent volume percent used was greater than ten percent.

Eleven of the 28 shots using FC-218 against the 110-grain fragment threat resulted in an explosion. FC-218 provided ullage protection with greater than four percent nominal concentration.

Weight And Cost Implications

Table 18 displays a subset of some of the critical agent properties previously mentioned.

Table 18. Agent Properties

Inerting Agent	Molecular Weight	Boiling Point at 1 atm (°F)	Critical Temperature (°F)	Liquid Density (g/ml)
Halon 1301	149	-72	154	1.05@70°F
FC-218	188.02	34.1	161.4	1.35@68°F
HFC-125	120.02	-54.7	151.25	1.189@77°F

The significance of these properties is presented below:

- Values such as liquid density, fill density, and specific volume determine how much more agent can be placed in the same size bottle.
- The agent boiling point is also an important value in determining how the agent may behave in certain environments.
- Molecular weight affects how stable the chemical is. Due to its higher molecular weight, FC-218 is a highly stable chemical.

Table 19 shows a preliminary weight and volume comparison of the two alternative agents investigated during this test program as compared with the weight and volume requirements for Halon 1301. The data for both Halon 1301 and FC-218 were obtained from *Version 4.0* of the *National Institute of Standards and Technology (NIST) Refrigerant Database*. The data for HFC-125 were obtained from the product manufacturer's literature.

As seen in this table, both alternative agents will require more volume. However, the FC-218 has less of a weight penalty. [7]

Table 19. Weight and Volume Requirements Of Alternative Agents

Agent	Concentration [C]	Molecular Weight	Liquid Density (lb/ft^3)	Weight Estimate	Volume Estimate	Fill Density (kg/m^3)
Halon 1301	6 %	149	98.65 @70 F	1.0	1.0	601
FC-218	5%	188.02	79.57 @70F	1.30	0.81	497
HFC-125	7%	120.02	74.27 @77F	1.25	1.03	458
HFC-125	10%	120.02	74.27 @77F	1.78	1.47	458

Effects On Other Aircraft Parameters

HFC-125 is easy to clean up. It leaves no residue in the event of accidental discharge. The pyrolysis products include HF and HCl. Some postfire clean up would be required. It is nonreactive with steel, aluminum, or brass. Minor swelling was evidenced in its contact with elastomers, such as Buna S, butyl rubber, and neoprene. No adverse effects are expected on plastics. Its atmospheric lifetime is 26.4 years. [41]

In *Perfluorocarbons (PFs) Fire/Explosion Suppressant Feasibility Study,* previous results provide comparisons between halon and FC-218. In this particular study using JP-4 against a 23mm HEI, the required concentrations were 20 percent and 28 percent for FC-218 and halon, respectively. Also in this same study, using a heptane-air mixture, the required concentrations were ten percent and six percent for FC-218 and Halon 1301, respectively.

Prior to making a definitive judgement, many factors must be considered which might affect the alternative agent selection. Issues related to the solubility, as well as the solubility rate of the agent in the fuel (how soluble the agent is in the fuel) may increase the total amount of fuel required which would increase the weight of the plane. In the work performed by Rodriguez et al, Halon 1301 was found to be five times as soluble in JP-4 as FC-218. Possible agent contamination of the fuel system must be evaluated prior to the agent selection. Any effects on engine performance must be comprehensively understood prior to agent selection. Any considerations/concerns regarding the effects of corrosion on the fuel system must be established and addressed prior to agent selection.

In the environmental conscious world in which we live, issues such as the global warming potential and ozone depleting potential of chemicals are very important. The Environmental Protection Agency has allowed both of the alternative agents presented here to be on the SNAP (Significant New Alternatives Program) list which allows them to be used as halon replacement chemicals. Background research (i.e., provide similar protection as halon, trade studies...) must be performed to substantiate their selection as alternatives.

The Environmental Protection Agency (EPA) requires that chemicals selected in the areas of fire suppression and explosion meet the requirements stipulated by 40 CFR Part 9 and 82—Protection of the Stratospheric Ozone). FC-218 is a very stable chemical and has a very long atmospheric life. Because of the emphasis on the problems associated with global warming, FC-218 may require approval from EPA prior to its selection. However, earlier discussions suggest that it would be acceptable if no other option works.

Given the high volatility, low water solubility and chemical stability of perfluoropropane, any amount released to the environment will partition almost entirely to the atmosphere where it is expected to prove at least as persistent as the more heavily fluorinated chlorofluorocarbons, which have estimated atmospheric residence times as high as 400 years.

Perfluoropropane contains no chlorine or bromine, and thus has zero ozone depletion potential.

Environmental properties of the chemicals studied in this F-16 test program are show in Table 20. [7]

Table 20. Environmental Properties of Inerting Agents

Inerting Agent	**Global Warming Potential (GWP)**	**Ozone Depleting Potential (ODP)**
Halon 1301	5600	10-14
FC-218	7000	$\cong 0$
HFC-125	2800	$\cong 0$

Current Status

DuPont was contacted to determine the status of the utilization of HFC-125 for fuel tank inerting. They stated that they have not performed any tests themselves with HFC-125. [43]

HFC-125 is used commercially in explosion suppression and is featured in the Fenwal Safety Systems X-PAC protection system. X-PAC systems stop grain elevator explosions by stopping flame propagation in a fraction of a second. [44]

3.2.3.14 Triodide (CF_3I)

Description/Types

The alternative agent that is the most similar to Halon 1301 (CF_3Br) is triodide (CF_3I). [41]

CF_3I has been recognized as an effective fire extinguishing agent and a potential "drop-in" replacement for Halon 1301 in some of the non-occupied applications. [45]

Capabilities And Limitations

The following results are from the F-16 fuel tank explosion suppression replacement and baseline characterization tests. These tests were conducted to allow development of alternative approaches to the current F-16 Halon 1301 fuel tank inerting system. [7] CF_3I was one of the candidate agents evaluated.

Weight And Cost Implications

CF_3I provided ullage protection with greater than six percent nominal concentration. [46]

Effects On Other Aircraft Parameters

Two characteristics have limited the acceptance of CF_3I:

- A relatively high boiling point (approximately -9°F for CF_3I vs. approximately -72°F for Halon 1301) and,
- The perceived health hazard associated with its relatively low toxicity/cardiac sensitization level (LOAEL approximately 0.4 percent for CF_3I vs. approximately 7.5 percent for Halon 1301.) [45]

Although CF_3I is as effective as Halon 1301 at suppressing fires, has almost zero ozone depleting potential (ODP) and is environmentally benign, it is a cardiac sensitizer. Therefore, the EPA has chosen to list CF_3I as a SNAP approved substitute in normally unoccupied areas. Aircraft engine nacelle fire suppression systems fall into this category. AF policy does not recommend the use of CF_3I in new systems.

Current Status

The AF has opted to continue research on CF_3I as a retrofit alternative for existing systems. [41] Preliminary analysis indicates CF_3I will be able to replace Halon 1301 with minor airframe system modifications. The F-16 airframe contractor is continuing to refine this analysis to an engineering manufacturing development status. [46]

3.2.3.15 Dry Powders

Description/Types

Dry chemicals are usually very effective in extinguishing fires and are often more effective than halons. Dry chemicals are suitable for Class A, B, and C fires, depending on the agent. They are often good halon substitutes where a range of different fire classes is possible. [41] Dry powders were first used in military aircraft as "powder panels" for dry bay protection.

Research shows that prevention of ullage explosions requires agent delivery to the flame front within about 20 milliseconds of HEI detonation.

Capabilities And Limitations

The limiting factor with powders is speed of delivery. Dry powder acts to halt propagation by attracting free radicals from the combustion components, thus preventing oxidant/oxidizer interaction. This is a rapid, effective means of explosion suppression. As powder effectiveness is governed by total exposed surface area of the power per unit weight; finer powders equate to increased effectiveness. In fuel tanks, the powder may have to travel some distance to reach the explosion flame front before it propagates. Elementary ballistics show that speed of delivery decreases with decreasing powder grain size due to velocity losses. Therefore, larger powder grains would be required to extinguish the ullage explosion before lethal overpressures are reached. These larger powder grain sizes would decrease the effectiveness of the powder in extinguishing the combustion once it got there. [11]

Dry powders only work if they are dry. Therefore, any ullage protection system will need appropriate packaging to assure a dry condition of the powder.

Weight And Cost Implications

No data were available at the time of this report.

Effects On Other Aircraft Parameters

Dry powders can, however, cause severe secondary damage to electronic and mechanical equipment and usually require major cleanup. [41]

Another drawback is engine and fuel system component damage, including corrosion and clogging of fuel system components as well as deposition and hot-metal corrosion in the hot section of the engine. These could occur if, after explosion-triggered or accidental discharge, particulate contaminated fuel from the tank is transferred through the fuel system and eventually to the engine. Because the ability of powders to suppress explosions is related to total surface area per unit weight, powders have been most effective at seven to ten micron particle sizes. This would pass through any filters currently used in aircraft fuel systems. Research indicates, however, that the powder would agglomerate, forming a sludge in the bottom of the fuel tank. However, it is probable that the agglomerated clumps of powder would be trapped in the fuel system filters. If the filters are plugged by the clumps, and the system reverts to bypassing the fuel around the filter, there is a possibility of clogging the engine fuel controls and combustor nozzles. During experimental dumping of large quantities of coarse Arizona road dust in the fuel supply of a General Electric F100-GE-100 engine, the engine tolerated as much dirt as there would be powder used. However, further testing with CFC-propelled dry powders would be appropriate and full system flushing after discharge would undoubtedly be required. [11]

In high performance aircraft, fuel is constantly being moved around as a part of the thermal management system. It is conceivable that some contaminated fuel could pass through pumps and valves, etc. more than one time with today's recirculation systems.

Current Status

Some of the most prominent dry powder candidates are sodium bicarbonate ($NaHCO_3$), which has been tested extensively under laboratory-scale conditions and potassium bicarbonate ($KHCO_3$). Sodium bicarbonate is slightly abrasive. It has insulating properties on electrical contacts and, in the presence of moisture, is corrosive to aluminum. It forms clouds when dispensed which obscure human vision as well as escape routes. It is nontoxic. Differing information was found regarding its corrosivity and its clean up. More sources need to be queried for a final verdict. [41]

Of all powders considered, research indicates Monoammonium Phosphate Powder (MAP) is the best for explosion suppression. It worked extremely well in the first LFE explosion suppression tests run at NWC. The U.S. Bureau of Mines Pittsburgh Research Center (PRC) has found that by mixing dry powder with a chlorofluorocarbon (CFC) propellant such as a halon or Freon, delivery speed of fine powders can be increased enough to suppress methane explosions before they trigger coal dust explosion in underground mines. However, Halon 1301 has an ODP of 14.3 and is currently on the Montreal list of substances scheduled for phase-out. Freon 23, however, has an ODP of zero, is a very effective propellant, and has some effectiveness as a fire suppressor (20 percent concentration required compared to four percent for Halon 1301).

KDKI is a powder consisting of potassium dawsonite (KD) iodized with potassium iodide (KI), plus a small amount of silica. Alkali dawsonites are co-crystallized compounds of an alkali metal and the dawsonite anion. When iodized, they produce superior fire-fighting capability compared to straight alkali metal carbonates, but with reduced corrosiveness. KDKI is a derivative of potassium bicarbonate (Purple-K) that has been shown to be more effective in fire suppression. While all available explosion suppression test results indicated that MAP is substantially superior to Purple-K, there is no comparable data on KDKI. Since KDKI is probably a more effective explosion suppressant than Purple-K, explosion testing of KDKI would fill a data gap. However, while KDKI is the test of the potassium carbonate-based powders as a fire suppressant, the difference between KDKI and Purple-K is small compared to the difference between MAP and Purple-K. It is unlikely that KDKI will compare favorably with MAP as an explosion suppressant. [11]

4.0 Technical Problems

Time and funding did not allow for a full scale evaluation and survey of nozzle manufacturers. Further effort should be expended to synchronize nozzle manufacturers with Parker Hannifin so that the PRESS technology can be fully exploited.

5.0 Recommendations

It is recommended that additional research should be performed to further explore the LFE and PRESS systems.

6.0 Conclusions

Of all the reactive systems investigated in this study, the LFE and the PRESS systems are the most viable. Investments into these technologies would not be futile.

At this time, the LFE is the most viable technology of the technologies investigated in this study.

At the present time, substantial investment would be required to make the other reactive technologies viable solutions.

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APPENDIX A

DOCUMENTS REVIEWED

REPORTS PERTINENT TO THIS EFFORT

	Report Number	Report Title
1		FAA ARAC FTHWG - Explosion Suppression Final Report, June 1998
2		FAA ARAC FTHWG - Fuel Tank Inerting Final Report, June 1998
3		FAA ARAC FTHWG - Service History/Fuel Tank Safety Level Assessment, July 1998
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6	SURVICE-TR-97-017	Ullage Explosion Hazard State of the Art Report, June 1997
7	SURVIAC-TR-89-021	Gas Explosion Suppression Agent Investigation, July 1989
8	JTCG/AS-89-T-005	Aircraft Fuel System Fire and Explosion Suppression Design Guide, February 1990
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11	JTCG/AS-90-T-0004	The Effectiveness of Ullage Nitrogen-Inerting Systems against 30-mm High Explosive Incendiary Projectiles, May 1991
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	Report Number	Report Title
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APPENDIX B

POINTS OF CONTACT

	Company/Organization	Point Of Contact	Phone #	Technology	Response/Comments
1	IDA	Vince Volpe	703/845-2309	OBIGGS Commanche helicopter (RAH-66)	RAH-66 and the special ops helicopters are making provisions for OBIGGS to inert the fuel tank ullages. He believes that the OBIGGS will be the molecular sieve type.
2	IDA	Ron Reece	703/845-6924	DDG51s and LHD/LHA1s	Indicated they mostly use Diesel Marine Fuel (DEM) and to his knowledge there is no ullage protection.
3	IDA	Ben Turner	703/845-6931	M1 (Abrams Tank), M2/M3 (Bradley Family Fighting Vehicle), and the M992 (Ordnance Artillery Supply Vehicle)	M1 and M2/M3 have a multifuel turbine engine that mostly runs on JP-8 fuel. They have automatic engine compartment and crew compartment fire suppression systems that currently use Halon 1301, however, they will be integrating in new agents. The M992 has a manual fire protection system using CO2.
4	United Aircraft Products, Division of Parker Membrane Separation System Air Liquide (MEDAL) (prime supplier for the F-22)	Karl Beers (MEDAL)	302-999-6037	OBIGGS (hollow fiber)	Their hollow fiber supplier is Membrane Separation System Air Liquide (MEDAL) in Newport, Delaware. MEDAL was an old division of DuPont.
5	Boeing, Philadelphia	Jim Ozimek Lead Engineer, Fuel Systems	610/597-4206	OBIGGS (molecular sieve)	V-22 does use a molecular sieve to provide nitrogen for fuel tank ullage protection.
6	Naval Weapons Center, China Lake, CA	Leo Budd	760 939-2181/2182	F/A-18E/F	The F/A-18E/F like the earlier models does not employ a fuel tank ullage protection system, however, this new model now has an automatic dry by fire suppression system which employs and IR detection and Solid State Gas Generators (SSGG).

U.S. GOVERNMENT AGENCIES AND THEIR CONTRACTORS ONLY

	Company/Organization	Point Of Contact	Phone #	Technology	Response/Comments
7	46 TW	Mike Bennett	255-6302 x 217	PRESS	23mm-HEI simulator was used at the Parker Hannifin site (similar pressure-time to 23mm HEI). Never got to use the W-Tank (ran out of money) Couldn't build complex nozzle due to such tight tolerances. Went back and used conventional nozzles in a radial fashion.
8	Applied Research Associates	Jim Tucker	255-6302 x 229	Passive ullage protection	Currently doing testing on passive ullage protection (metal mesh). The upcoming test program will not only address the LFE, but will also attempt to characterize the reactive loads applied to the aircraft structure as a result of LFE activation. During the original tests, the loads occurred so quickly that they were not captured by the instrumentation. The effects were also not obvious due to the robustness of the test article used. However, when the system was tested on an air raft structure, the reaction load effects were evident. Some "quick fix" methods were attempted to mitigate the reaction load. These included the use of shock absorbers (but the natural frequency was too low) and putty. With the upcoming testing, these reactive loads will be quantified, if possible. In possible later studies, methods to mitigate these loads will be explored. For the upcoming testing several agents may be tested and include CF3I and a fuel (propane/butane). The alternate agents have not been selected because the
9	E. Raymond Lake Company	Ray Lake	314-771-1236		Information re: NIBB, OBIGGS, LFE, PRESS
10	BlazeTech Corporation	Dr. Albert Moussa		Fuel tank bubbler	Hydrodynamic ram and ullage explosion

	Company/Organization	Point Of Contact	Phone #	Technology	Response/Comments
11	Zvezda	Dr. Klemenko			Not able to be reached. However, Mr. J. Michael Bennett (46TW) provided the information regarding the Russian system.
12	AFP Associates	Robert Clodfelter	937-435-8778		Provided information regarding the Walter Kidde Canister system. The F-105 aircraft used plastic spheres filled with Halon 1301. The spheres would fracture and distribute the agent. Disadvantages included a propensity for false alarms as well as the sphere fragments being released into the fuel system.
13	Parker Hannifin	Chuck Clark	606-269-2351	PRESS	"Ball park" cost estimates were performed and showed that the system would be fairly expensive. Another issue was the installation of the PRESS system in small compartments. The installation would be difficult and costly. Also detection would be difficult since the detectors were line of sight. Parker Hannifin representatives stated that the PRESS technology has been shelved due to technical and funding issues. The technical issues included the nozzle technology development. Several different approaches were attempted. In their opinion, nozzle technology has not advanced to a state that would allow the PRESS technology to be further pursued by Parker Hannifin. The funding issues, as previously stated, prohibited the investigation of this system at the WPAFB ASRF.
14	Boeing	Jamie Childress		NIBB	Will look for report. No response was received. He also mentioned contacting Rick Luzetsky at Boeing-Philadelphia for this information.

	Company/Organization	Point Of Contact	Phone #	Technology	Response/Comments
15	DuPont	Dan Moore	1-800-441-8140	HFC-125	Amongst our offerings I would select FE-25 (HFC-125) for inerting because of its stability and low boiling point. However we have not done any testing. I do know that Kidde Technologies sells FE-25 systems for explosion suppression in grain elevators. No doubt they have some test work to support this. Joe Senecal at Kidde-Fenwal may be able to help you further. At a NMERI conference a couple of years ago I heard that the Air Force preferred a perfluorocarbon to FE-25 because it had lower solubility in the fuel. However perfluorocarbons are fading so FE-25 might be in the running again. We have had some discussions with NAVAIR relative to the stability of FE-25 in engine nacelle fire protection situations and the latest I have heard is that they have satisfied their critics. For more information contact Don Bein. From our perspective the best news about FE-25 derives from the recent PBPK data which makes it viable for occupied areas as long as exposure is limited to 11 1/2% for 5 minutes.
16	Newhouse International	Steve Newhouse	714-685-9920	CF3I	Sent email request for information. No response was obtained.
17	Kidde Graviner	David Ball	011-44-753-683245		Sent email request for information. No response was obtained.
18	Kidde Aerospace and Defense		919-237-7004	extinguisher mfg	Sent email request for information. No response was obtained.
19	Walter Kidde Aerospace			Canister System	Sent email request for information. No response was obtained.

	Company/Organization	Point Of Contact	Phone #	Technology	Response/Comments
20	Kidde Fenwal	Dr. Joe Senecal	508-881-2000, extension 2772	extinguisher mfg	Kidde Fenwal does no work in relation to aircraft fuel tank explosion protection. He forwarded my request to Fenwal Safety Systems and to Walter Kidde Aerospace, however no response was ever received.
21	Pacific Scientific	Bill Meserve	626-359-9317		Sent email request for information. No response was obtained.
22	Primex	Paul Wierenga	425-885-5000	gas generator	Provided documents describing two approaches that Primex presented to a FAA ARAC committee several years ago. One is a passive approach and the other is a reactive approach. Both are feasible. However, no further development has been conducted on either. Neither the DoD nor the Commercial Airframers seems particularly interested in developing a solution. The reactive approach could be implemented using solid propellant fire extinguishers, hybrid (any agent) or a rapid (very, very rapid) deluge blowdown system. Ullage testing was conducted at China Lake in the mid 90s with the objective of demonstrating ullage protection against large ballistic projectile threats (30 mm HEI) in a fighter type aircraft configuration. The testing was successful. China Lake (Hardy Tyson) did quite a bit of work in this field in the early 90s. Primex was actually awarded an NGP project to pursue our passive carbon bed approach. Unfortunately, they never received any money to conduct the work. Thus, the effort was never completed.

	Company/Organization	Point Of Contact	Phone #	Technology	Response/Comments
23	Meggitt Safety	Frank Bosworth	805-584-4100 x 8134	LFE	Testing is schedule to begin in April 2000 @ WPAFB. 40-70 LFT shots. Several agents and several threats will be tested. The POC is Jim Tucker. The testing objective includes testing the: device, halon alternative, and the loads imposed on the structure. Not really any maintenance issues since it was never a fielded system. Not really any specific logistical concerns, however, it is different than other devices. The handling of agents may incur some logistical considerations. It is a pressure vessel and should be treated as such. It is believed that it will/can go on existing aircraft. No cost studies have been performed. It is recognized that there are reactive loads imposed on the aircraft structure. These loads occur within 1 millisecond. Need to look at ways to attenuate those loads.
24	BP	David Catchcole	907-868-3911	Explosion suppression devices	BP in Alaska has never been involved with fuel tank explosion suppression. Their interest lies in explosion prevention in large buildings, which is not the same. However, BP has a research facility in the UK that may have done some work in this area so he sent the request on.

	Company/Organization	Point Of Contact	Phone #	Technology	Response/Comments
25	Boeing, Seattle	Tom Reynolds	425-342-6464	TALON system	NASA (Glenn Research Center – Aviation Systems) in tandem with Boeing, Seattle and the FAA are investigating the TALON system. AFRL (Brooks, AFB) has investigated TALON for its generation of oxygen for MEDIVAC missions. The oxygen is used for the crew and patients and paratroop requirements. Current efforts by the previously mentioned consortium are investigating the use of TALON for its nitrogen generation for fuel tank inerting for both commercial and military requirements.
26	BP	Vincent Tam			BP in the UK has been looking at explosion suppression technology for application to offshore production platforms and has developed a strategy to identify and evaluate appropriate technology. We deliberately stay away from 'chemical' solutions to avoid impact on people. Apart from that our approach is not too dissimilar to the description in your email, perhaps the only difference is in the application of numerical modeling in enhancing and optimizing the technology. The systems we looked at which could be applicable to your project are: chemical powder based (there are numerous manufacturers, e.g. Kidde, Fike, Stuvex), fine water mist (e.g. Ginger Kerr), Hot water technology (Micromist). This system relies on different discharge nozzle technology and detection and control system. My suggestion is that for your applications, the 'built-in' detection and control may not be appropriate, and the testing could bypass them with a purpose-built detection and control system.

	Company/Organization	Point Of Contact	Phone #	Technology	Response/Comments
27	NMERI	Barbara Daniels	505-272-7250		The following report could not be obtained since it was performed for a client. JTCG/AS-90-T-003 - Fire/Explosion Protection Characterization and Optimization: Phase II Alternative Dry Bay Fire Suppression Agent Screening Everett W. Heinonen, Ted A. Moore, Jonathan S. Nimitz, Stephanie R. Skaggs, and Harold D. Beeson; New Mexico Engineering Research Institute, The University of New Mexico, Albuquerque, NM. October 1990

APPENDIX C

ALTERNATIVE TECHNOLOGY DATABASE

Point of Contact	Frank Bosworth – Meggitt Safety Systems
Military Service (U.S. Air Force, U.S. Navy, U.S. Army)	U.S. Navy
Date of Development	1985
Technology Developed	Linear Fire Extinguisher
Mechanisms Used (How It Operates)	Uses linear shaped charges to disperse the extinguishant
Ability to Withstand the Fuel Tank Operating Environment	N/A
Maintenance Impact	• The detonator has a definite service life. The predicted life from the date of manufacture is 10 years, which consists of up to four years of storage and six years of installed service. The detonators will require replacement just before their service life expires. • Activation of this system with maintenance personnel in the tank presents a hazard of serious injury.
Logistics Concerns	Possible effects on flight safety, crashworthiness, and other capabilities are unlikely but as yet unknown.
Technological Challenges (Why Development Not Completed, Loss of Funding)	Funding has never been stable.
Status of Development (Initial, Validation, Fielded)	Initial
System Initial and Support Costs	Cost will therefore be somewhat dependent upon the tank's configuration and its internal complexities. Only rough order of magnitude costs of procurement, have been evaluated.
Retrofit Impact (Costs, Integration Difficulties)	
Requirements Impact (Weight, Volume, Power, Fuel Quantity Reduction…)	System weight will depend on the size and shape of each fuel tank. The only range impact would be carrying the additional weight of the system.
Suppressant/Technology Utilized (Halon-Type, Water, Liquid, Gas…)	Water/AFFF/water; water/ AFFF/Halon 1301; water/MAP; 30 percent calcium chloride/water solution; 50 percent ethylene glycol/water solution; 70 percent ethyl alcohol/water solution; Halon 1301/water mixture, propane; and MAP/Halon 1301 FC-218, HFC-227ea, HFC-125, and pentane
Expulsion Method (Utilization of Nitrogen, Nozzles…)	The FLSC detonates, directing a shock wave and ultra-high-pressure plasma "jet" along the length of the tube forming the primary cutting action that opens the tube. The superpressurization extinguishant is then pushed out of the opened tube, filling the protected compartment.
Effectiveness (Vs. Threat, Environment…) – list the threats tested	30mm HEI. Limited testing with the .50-cal API, 12.7-mm API and 23mm HEI was also conducted.
Restart Funding Required (Cost to Reevaluate the "Moth-balled" Technology)	N/A – This technology has been around over the past 15 years. It is scheduled to be tested at WPAFB in June 2000.
Testing Performed (Small- Medium- Large-Scale)	Large-scale
More advanced versions/technologies which now make it feasible (technological breakthrough)	Mitigate reaction loads.
Recommended for specific type of aircraft (fighter/attack, bomber, cargo/transport)	Suitable for large fuselage tanks.

Point of Contact	Chuck Clark - Parker Hannifin
Military Service (U.S. Air Force, U.S. Navy, U.S. Army)	U.S. Air Force
Date of Development	Late 1980s – early 1990s
Technology Developed	Parker Reactive Explosion Suppression System (PRESS)
Mechanisms Used (How It Operates)	high pressure expulsion force expels the adjacent bladder filled with water. The water exits through orifice holes, is transmitted through radial channels in the external nozzles and released as 5-micron-thick sheets. These sheets break up into 10-micron droplets.
Ability to Withstand the Fuel Tank Operating Environment	N/A
Maintenance Impact	Use of explosives and chemical propellants inside fuel tanks to suppress a fuel explosion initially causes concerns.
Logistics Concerns	• Installation of PRESS in small compartments would be difficult and costly. • Reduced system down time, elimination of between sortie servicing, and elimination of logistics for consumables. • Compared to foam, unobstructed access to fuel cells will reduce fuel system downtime for maintenance.
Technological Challenges (Why Development Not Completed, Loss of Funding)	Technology has been shelved due to technical and funding issues. The technical issues included the nozzle technology development. The funding issues prohibited the investigation of this system at the WPAFB ASRF.
Status of Development (Initial, Validation, Fielded)	Initial.
System Initial and Support Costs	"Ball park" cost estimates were performed and showed that the system would be fairly expensive.
Retrofit Impact (Costs, Integration Difficulties)	• Installation of PRESS in small compartments would be difficult and costly. Detection would be difficult since the detectors were line of sight. • Retrofit into existing aircraft is feasible because the system can be designed to be installed entirely within fuel tanks, through existing tank access doors. • Electrical wiring, for standard aircraft power and desired diagnostic information from the explosion sensor built-in-test, is all that is required outside of fuel tanks. Displacement of fuel will be less than 0.1 percent. However, brackets and electrical wiring may require fuel tank penetration.
Requirements Impact (Weight, Volume, Power, Fuel Quantity Reduction…)	Advantages of dual slit nozzle configurations were recognized. There are indications that the speed of delivery of initial suppressant into the fire is not as critical as originally thought. This confirms a potential for reducing projected system weight.
Suppressant/Technology Utilized (Halon-Type, Water, Liquid, Gas…)	Water with dissolved 31.4 percent by weight $CaCl_2$ to reduce its freezing temperature to below –65°F.
Expulsion Method (Utilization of Nitrogen, Nozzles…)	Nozzles
Effectiveness (Vs. Threat, Environment…) – list the threats tested	The proof-of-concept tests have shown the system to successfully reduce the overpressure created by a 23mm HEI simulator detonated within an explosive propane air mixture in an experimental tank. Although optimization of the nozzle configuration was not fully attained, ullage pressure that would have reached 100 psi in 10 milliseconds, when not suppressed, was limited to below the objective during three tests. The PRESS approach showed it is possible to react fast enough to control the ullage pressure rise caused by simulated HEI ignition of a stoichiometric fuel vapor-air mixture. Although not enough empirical data were developed to fully understand the suppression process, it was shown that the process response to nozzle configurations is repeatable.
Restart Funding Required (Cost to Reevaluate the "Moth-balled" Technology)	The funding issues prohibited the investigation of this system at the WPAFB ASRF.
Testing Performed (Small- Medium- Large-Scale)	Medium scale
More advanced versions/technologies which now make it feasible (technological breakthrough)	Nozzle technology has not advanced to a state that would allow the PRESS technology to be further pursued by Parker Hannifin.
Recommended for specific type of aircraft (fighter/attack, bomber, cargo/transport)	N/A

Point of Contact	Mr. David Ball – Kidde International
Military Service (U.S. Air Force, U.S. Navy, U.S. Army)	System used by British Air Force, U.S. Air Force and Navy
Date of Development	1950s
Technology Developed	Scored-Canister System (SCS)
Mechanisms Used (How It Operates)	Each SCS suppressor is composed of a scored, frangible hemisphere filled with a liquid-phase suppressant. The explosive "blast" couples to the scored frangible wall of the hemisphere, which fails along the score lines. The explosive energy expels the suppressant as a cloud of spray, made up of fine droplets, that expands into the fuel-tank ullage.
Ability to Withstand the Fuel Tank Operating Environment	The suppressor units are not pressurized and are suitable for operating under negative-pressure excursions within temperatures ranging from –35 to +60°C.
Maintenance Impact	No safety problems are known. To avoid any hazard related to tank overpressure associated with the discharge of the system, it is designed to sense fuel level and discharge the amount of suppressant required by the ullage volume present. To avoid or minimize the addition of wiring within the tank, the design can provide for sensors mounted against the inside surface of outside tank walls with wiring outside the tank. For any suppressors that can not be mounted on outside tank walls, wiring for suppressor initiation at momentary five amps per suppressor, must be housed in conduits inside the tank. Inadvertent system operation has occurred with early type sensors. This is not expected with the later technology sensors presently being used. The observance of proper in-tank maintenance procedures is necessary with any such systems and must include system disarming prior to tank entry for maintenance.
Logistics Concerns	The sensors and hemispherical type suppressors could be located in the ullage. Therefore, no fuel volume reduction would occur and no increase in landings due to range reduction or additional fuel consumption would be expected.
Technological Challenges (Why Development Not Completed, Loss of Funding)	Problem with false alarms from early sensors.
Status of Development (Initial, Validation, Fielded)	Initial
System Initial and Support Costs	The installation labor costs per aircraft are estimated to range from $7,000 to $17,000 if accomplished during scheduled maintenance while fuel tanks are open and are based on a labor rate of $45 / m-hr. There are no known system operational costs. Unscheduled maintenance costs, comprised of costs of delays, cancellations, out-of-service time, and maintenance man-hours and materials, have not been determined due to lack of reliability data. Detonator replacement is estimated to be required at 10 year intervals and would occur at major maintenance cycles; however, the material cost is not available.
Retrofit Impact (Costs, Integration Difficulties)	N/A
Requirements Impact (Weight, Volume, Power, Fuel Quantity Reduction…)	The system weights could be reduced if the system can be made efficient by localizing the protected area.
Suppressant/Technology Utilized (Halon-Type, Water, Liquid, Gas…)	Pentane and Halon 1101
Expulsion Method (Utilization of Nitrogen, Nozzles…)	Explosive devise fractures hemispherical head.
Effectiveness (Vs. Threat, Environment…) – list the threats tested	SCSs filled with pentane to provide a 47% concentration (approximately 54% mass fraction) suppressed explosions in a 30 cubic-foot (ft^3) volatile ullage simulator initiated by both a single 110-grain fragment and a 12.7-mm API. Partial suppression only was realized against the 23-mm HEI in that the peak pressure was limited to 40 psig.
Restart Funding Required (Cost to Reevaluate the "Moth-balled" Technology)	N/A
Testing Performed (Small- Medium- Large-Scale)	Large scale
More advanced versions/technologies which now make it feasible (technological breakthrough)	Newer sensors would allow for this technology to be reanalyzed.
Recommended for specific type of aircraft (fighter/attack, bomber, cargo/transport)	N/A

Point of Contact	Mr. Paul Wierenga – Primex Aerospace Company
Military Service (U.S. Air Force, U.S. Navy, U.S. Army)	U.S. Navy
Date of Development	Initially developed portable extinguishers late 1950s, for use on engine nacelles in the early 1960s, for dry bay applications in the early 1990's.
Technology Developed	Solid Propellant Gas Generators
Mechanisms Used (How It Operates)	electrically initiated, exothermic reaction releasing carbon dioxide, nitrogen, water and trace compounds
Ability to Withstand the Fuel Tank Operating Environment	Development testing is still necessary to characterize a gas generator system that is compatible with today's aircraft and their requirements.
Maintenance Impact	If the system were activated with personnel in the tanks, this could result in serious injury. Therefore, the system would have to be deactivated prior to any entry into the fuel tank. No other equipment hazards or effects have been identified.
Logistics Concerns	N/A
Technological Challenges (Why Development Not Completed, Loss of Funding)	Putting pyrotechnic devices (squib or pyrotechnic initiators) into the tank may present a risk to the aircraft. A full safety analysis would be required to determine the resulting level of safety for the system. Presumably, the fact that an explosion suppressant would be released if the squib was activated would ensure any ensuing explosion would be suppressed.
Status of Development (Initial, Validation, Fielded)	Initial
System Initial and Support Costs	Only the cost of procurement has been evaluated. Since the complete system (sensor and gas generators) has not been demonstrated effective in suppressing fuel tank explosions, a complete cost analysis was not performed.
Retrofit Impact (Costs, Integration Difficulties)	N/A
Requirements Impact (Weight, Volume, Power, Fuel Quantity Reduction…)	Weight estimates for commercial aircraft utilizing a gas generation technology are given below. The weight estimates are for the total tank volume, main and center wing tank. The bizjet tank volume is shown as 2,000 gallons, but the standard volume is 1,200 gallons. The weights are quite low for all models compared to other methods such as foam and nitrogen inerting. Any aircraft structural changes are not shown but would be minor. The canisters are one to two inches in diameter and up to one foot long and would occupy a minimal tank volume. The controller located outside of the tank would occupy a small volume and would require no modifications to the airplane to install. The only range impact would be carrying the additional weight shown in Table 10.
Suppressant/Technology Utilized (Halon-Type, Water, Liquid, Gas…)	exothermic reaction releasing carbon dioxide, nitrogen, water and trace compounds
Expulsion Method (Utilization of Nitrogen, Nozzles…)	pyrotechnic devices
Effectiveness (Vs. Threat, Environment…) – list the threats tested	The gas generation technology has been successfully shown in live fire testing to protect a fuel tank from catastrophic overpressure resulting from API threats, but was to slow to protect a fuel tank against a 23mm HEI.
Restart Funding Required (Cost to Reevaluate the "Moth-balled" Technology)	N/A
Testing Performed (Small- Medium- Large-Scale)	Large scale
More advanced versions/technologies which now make it feasible (technological breakthrough)	N/A
Recommended for specific type of aircraft (fighter/attack, bomber, cargo/transport)	N/A

Point of Contact	Mr. Jamie Childress – The Boeing Company, Seattle
Military Service (U.S. Air Force, U.S. Navy, U.S. Army)	U.S. Navy
Date of Development	N/A
Technology Developed	Nitrogen-Inflated Ballistic Bladder System (NIBBS)
Mechanisms Used (How It Operates)	As the fuel is used, the self-sealing inflatable bladders inflate with nitrogen, thus, eliminating the ullage space and producing a protective, inerted air gap between the fuel and the adjacent dry bay. The bladders are semi-permeable, so as they reach the limit of their distension, the nitrogen flows into the growing ullage space, providing inerting to prevent an explosion.
Ability to Withstand the Fuel Tank Operating Environment	N/A
Maintenance Impact	There are some maintainability penalties, but the fuel penalties are very small (limited to the thickness of the uninflated bladder). This is probably the most advanced and complete ullage explosion hazard system.
Logistics Concerns	N/A
Technological Challenges (Why Development Not Completed, Loss of Funding)	N/A
Status of Development (Initial, Validation, Fielded)	N/A
System Initial and Support Costs	N/A
Retrofit Impact (Costs, Integration Difficulties)	N/A
Requirements Impact (Weight, Volume, Power, Fuel Quantity Reduction…)	N/A
Suppressant/Technology Utilized (Halon-Type, Water, Liquid, Gas…)	nitrogen
Expulsion Method (Utilization of Nitrogen, Nozzles…)	Utilization of nitrogen via semi-permeable bladders
Effectiveness (Vs. Threat, Environment…) – list the threats tested	The system is in development and has been tested against API and HEI projectiles. However, no information on its effectiveness was available.
Restart Funding Required (Cost to Reevaluate the "Moth-balled" Technology)	N/A
Testing Performed (Small- Medium- Large-Scale)	Large-Scale
More advanced versions/technologies which now make it feasible (technological breakthrough)	N/A
Recommended for specific type of aircraft (fighter/attack, bomber, cargo/transport)	N/A

Point of Contact	Bill Meserve – Pacific Scientific
Military Service (U.S. Air Force, U.S. Navy, U.S. Army)	U.S. Army
Date of Development	N/A
Technology Developed	Pacific Scientific
Mechanisms Used (How It Operates)	N/A
Ability to Withstand the Fuel Tank Operating Environment	N/A
Maintenance Impact	Since the inadvertent firing of the agent when personnel are in the tank is a potential threat, the system would be de-energized before entering the tank.
Logistics Concerns	N/A
Technological Challenges (Why Development Not Completed, Loss of Funding)	The safety of discharging into a variable ullage volume and possible discharges under the fuel would have to be demonstrated. Possible wing overpressurization could result if the system designed for an empty tank discharges into a full tank. Also, the hydraulic ram effect of discharging the agent under the fuel could cause the tank to rupture. Possible tank overpressure could result from the discharge of agent sized for an empty tank when the tank is full. Also the hydraulic ram effect if the agent is discharged under the fuel could rupture the tank.
Status of Development (Initial, Validation, Fielded)	Pacific Scientific does not manufacture and have not tested explosion suppression systems for fuel tanks. Other Pacific Scientific fire suppression systems have been qualified in military applications. However, the effectiveness of this technology for fire suppression in fuel tanks has not been demonstrated or determined.
System Initial and Support Costs	N/A
Retrofit Impact (Costs, Integration Difficulties)	N/A
Requirements Impact (Weight, Volume, Power, Fuel Quantity Reduction…)	No weight estimates were developed, since the applicability of this technology is not known for explosion suppression in fuel tanks. No detailed design was performed, and no weight data was submitted. Furthermore, no sizing estimates were developed.
Suppressant/Technology Utilized (Halon-Type, Water, Liquid, Gas…)	N/A
Expulsion Method (Utilization of Nitrogen, Nozzles…)	N/A
Effectiveness (Vs. Threat, Environment…) – list the threats tested	Pacific Scientific does not manufacture and have not tested explosion suppression systems for fuel tanks. Other Pacific Scientific fire suppression systems have been qualified in military applications. However, the effectiveness of this technology for fire suppression in fuel tanks has not been demonstrated or determined.
Restart Funding Required (Cost to Reevaluate the "Moth-balled" Technology)	None of the Pacific Scientific components or systems has been tested in a wet-bay. A significant amount of additional development and testing to provide adequate protection in this environment is needed. For a complex aircraft fuel system, additional development for alternate, more suitable suppressants, and microprocessor controllers to deal with multiple bottle arrays and variations in ullage volume must be conducted to minimize any overpressure hazard.
Testing Performed (Small- Medium- Large-Scale)	Pacific Scientific does not manufacture and have not tested explosion suppression systems for fuel tanks. Other Pacific Scientific fire suppression systems have been qualified in military applications. However, the effectiveness of this technology for fire suppression in fuel tanks has not been demonstrated or determined.
More advanced versions/technologies which now make it feasible (technological breakthrough)	N/A
Recommended for specific type of aircraft (fighter/attack, bomber, cargo/transport)	N/A

Point of Contact	N/A
Military Service (U.S. Air Force, U.S. Navy, U.S. Army)	U.S. Bureau Of Mines
Date of Development	N/A
Technology Developed	Explosion Suppression Systems
Mechanisms Used (How It Operates)	Triggered and Passive Barriers –Triggered barriers typically consist of a flame sensor, disperser, and extinguishing agent. The flame sensor activates the disperser, which rapidly releases the agent stored under pressure.
Ability to Withstand the Fuel Tank Operating Environment	N/A
Maintenance Impact	Clean up issues associated with dry powders.
Logistics Concerns	N/A
Technological Challenges (Why Development Not Completed, Loss of Funding)	N/A
Status of Development (Initial, Validation, Fielded)	Initial
System Initial and Support Costs	N/A
Retrofit Impact (Costs, Integration Difficulties)	N/A
Requirements Impact (Weight, Volume, Power, Fuel Quantity Reduction…)	N/A
Suppressant/Technology Utilized (Halon-Type, Water, Liquid, Gas…)	• Inhibitors consisted of rock dust ($CaCO_3$), BCD ($NaCl$), Super K (KCl), Purple-K ($KHCO_3$), BCS ($NaHCO_3$), ABC ($NH_4H_2PO_4$), water, hybrids of water plus Halon 1301 (CF_3Br) or low-expansion foam plus Halon 1301, pure Halon 1301, ABC (ammonium phosphate), water and ABC powder (ammonium phosphate)
Expulsion Method (Utilization of Nitrogen, Nozzles…)	Triggered barriers rapidly release the agent stored under pressure.
Effectiveness (Vs. Threat, Environment…) – list the threats tested	• The suppressants performed in the following manner: $NH_4H_2PO_4$ > Halon 1301 > aqueous foam or water combined with Halon 1301 > Water > $NaCl$ > KCl >> $NaHCO_3$ > $CaCO_3$ > $KHCO_3$. • The limiting factor with powders is speed of delivery. As powder effectiveness is governed by total exposed surface area of the power per unit weight, finer powders equate to increased effectiveness. However, in fuel tanks, the powder may have to travel some distance to reach the explosion flame front before it propagates. Elementary ballistics show that speed of delivery decreases with decreasing powder grain size due to velocity losses. Therefore, larger powder grains would be required to extinguish the ullage explosion before lethal overpressures are reached. These larger powder grain sizes would decrease the effectiveness of the powder in extinguishing the combustion once it got there. • Mixing dry powder with a CFC propellant increases the delivery speed of fine powders enough to suppress methane explosions before they trigger a coal dust explosion
Restart Funding Required (Cost to Reevaluate the "Moth-balled" Technology)	N/A
Testing Performed (Small- Medium- Large-Scale)	N/A
More advanced versions/technologies which now make it feasible (technological breakthrough)	N/A
Recommended for specific type of aircraft (fighter/attack, bomber, cargo/transport)	N/A

Point of Contact	N/A
Military Service (U.S. Air Force, U.S. Navy, U.S. Army)	N/A
Date of Development	N/A
Technology Developed	Gas Research Institute Explosion Suppression Information
Mechanisms Used (How It Operates)	Small, stationary, dry chemical ($KHCO_3$) systems with automatic flame, automatic heat or visual detection offer the means for rapid suppression with less interference with escape.
Ability to Withstand the Fuel Tank Operating Environment	N/A
Maintenance Impact	N/A
Logistics Concerns	N/A
Technological Challenges (Why Development Not Completed, Loss of Funding)	N/A
Status of Development (Initial, Validation, Fielded)	N/A
System Initial and Support Costs	N/A
Retrofit Impact (Costs, Integration Difficulties)	N/A
Requirements Impact (Weight, Volume, Power, Fuel Quantity Reduction…)	N/A
Suppressant/Technology Utilized (Halon-Type, Water, Liquid, Gas…)	dry chemical ($KHCO_3$)
Expulsion Method (Utilization of Nitrogen, Nozzles…)	N/A
Effectiveness (Vs. Threat, Environment…) – list the threats tested	The effectiveness of dilution or removal of escaping gas is not established because accident reports do not quantify the leak rate.
Restart Funding Required (Cost to Reevaluate the "Moth-balled" Technology)	N/A
Testing Performed (Small- Medium- Large-Scale)	N/A
More advanced versions/technologies which now make it feasible (technological breakthrough)	N/A
Recommended for specific type of aircraft (fighter/attack, bomber, cargo/transport)	N/A

Point of Contact	Dr. Alexander Klemenko – Zvezda (a Russian survivability company)
Military Service (U.S. Air Force, U.S. Navy, U.S. Army)	Russian Air Force
Date of Development	N/A
Technology Developed	Zvezda Halon 2402 Reactive Explosion Suppression System
Mechanisms Used (How It Operates)	A Halon 2402 system was used as a helicopter fuel tank protection. It has a hemispherical head that explodes upon detection of an incendiary by a photo detector. Halon 2402 was expelled as a liquid and did not present a potential for overpressurizing the tank.
Ability to Withstand the Fuel Tank Operating Environment	N/A
Maintenance Impact	N/A
Logistics Concerns	N/A
Technological Challenges (Why Development Not Completed, Loss of Funding)	Halon 2402 is very toxic.
Status of Development (Initial, Validation, Fielded)	Fielded
System Initial and Support Costs	N/A
Retrofit Impact (Costs, Integration Difficulties)	N/A
Requirements Impact (Weight, Volume, Power, Fuel Quantity Reduction…)	N/A
Suppressant/Technology Utilized (Halon-Type, Water, Liquid, Gas…)	Halon 2402.
Expulsion Method (Utilization of Nitrogen, Nozzles…)	Expelled as a liquid.
Effectiveness (Vs. Threat, Environment…) – list the threats tested	No data were available at the time of this report.
Restart Funding Required (Cost to Reevaluate the "Moth-balled" Technology)	No data were available at the time of this report.
Testing Performed (Small- Medium- Large-Scale)	Large scale
More advanced versions/technologies which now make it feasible (technological breakthrough)	The use of halon alternatives in this system may be possible since some of them have high boiling points like Halon 2402.
Recommended for specific type of aircraft (fighter/attack, bomber, cargo/transport)	helicopter

Point of Contact	Several manufacturers – one example is Parker Hannifin
Military Service (U.S. Air Force, U.S. Navy, U.S. Army)	U.S. Air Force
Date of Development	OBIGGS has been tested from the early 1970s to the present. Air Force interest in the OBIGGS concept dates back to the 1960s.
Technology Developed	Onboard Inert Gas Generator Systems (OBIGGS)
Mechanisms Used (How It Operates)	Processes high pressure engine bleed air and produces an air supply that has had oxygen removed, resulting in a higher percentage of nitrogen referred to as NEA. The NEA is then either used in an on-demand mode or stored mode, while the waste product is usually vented out of the aircraft.
Ability to Withstand the Fuel Tank Operating Environment	OBIGGS type inerting systems are currently used on military aircraft.
Maintenance Impact	• The passive nature of the permeable membranes translates directly into high reliability. At the present time, there are no apparent significant effects of OBIGGS upon flight safety, crashworthiness, maintainability, or repairability. • On-demand systems are more reliable than the stored gas systems and can inert for any mission if designed for maximum descent rate. The on-demand system drawbacks include a large ASM, increased system cycles for multiple descents (higher failure rate), possible sizing effects of ECS, and the possibility of NEA demand that exceeds capacity (emergency descents). Operational compromises will almost certainly be required. Many of today's aircraft do not have enough bleed air available to supply these systems. • Gaseous inerting agents present a suffocation hazard, and liquid nitrogen presents the additional hazards of freezing trauma to skin and eyes. • The reliability (maintainability) of the Air Separation Module is a problem. The valves and sensors had a high degree of reliability. Overall system reliability was said to be <200 hours between failures and <100 hours between maintenance.
Logistics Concerns	N/A
Technological Challenges (Why Development Not Completed, Loss of Funding)	N/A – This is a technology currently being developed.
Status of Development (Initial, Validation, Fielded)	Fielded. OBIGGS type inerting systems are currently used on military aircraft, notably the C-17 as well as some fighters (i.e., F-117, F-22) and helicopters (i.e., CH-47 E (special operations), V-22, RAH-66).
System Initial and Support Costs	A life cycle cost (LCC) comparison was also made for the fighter sized system. The LCC results are in constant 1985 dollars. The stored gas system had the lowest cost. Similar comparisons have been made for larger aircraft such as the C-5B. The stored gas system (as used on the C-5A) required the Air Force to build cryogenic nitrogen storage sites at key bases around the world. This was not a small investment. The projected life cycle costs for the stored gas system were estimated at \$523M compared to \$561M for an on-demand system, \$575M for an LN_2 system, and \$824M for a foam system (78 percent of the cost was in fuel penalties).
Retrofit Impact (Costs, Integration Difficulties)	N/A
Requirements Impact (Weight, Volume, Power, Fuel Quantity Reduction…)	The stored gas system weighed only 258 lb. compared to the 365 lb. on-demand system.
Suppressant/Technology Utilized (Halon-Type, Water, Liquid, Gas…)	Inert gas (nitrogen).
Expulsion Method (Utilization of Nitrogen, Nozzles…)	Utilization of Nitrogen
Effectiveness (Vs. Threat, Environment…) – list the threats tested	Either the MS or PM system provides the necessary protection for a fighter type aircraft and could compete with other protective techniques.
Restart Funding Required (Cost to Reevaluate the "Moth-balled" Technology)	N/A – This is a technology currently being developed.
Testing Performed (Small- Medium- Large-Scale)	All.
More advanced versions/technologies which now make it feasible (technological breakthrough)	N/A – This is a technology currently being developed.
Recommended for specific type of aircraft (fighter/attack, bomber, cargo/transport)	The application of an OBIGGS system to fighter size aircraft, which would also approximate helicopters, is the most demanding due to the relative size and rapid rates of descent experienced by fighter aircraft.

Point of Contact	Mr. Tom Reynolds – Boeing, Seattle
Military Service (U.S. Air Force, U.S. Navy, U.S. Army)	NASA (Glenn Research Center – Aviation Systems), Boeing, Seattle, FAA, U.S. Air Force Research Laboratory (Brooks, AFB)
Date of Development	1990s
Technology Developed	Total Atmospheric Liquification of Oxygen and Nitrogen (TALON)
Mechanisms Used (How It Operates)	Self generates, stores, and delivers high purity oxygen (ninety-nine percent) and nitrogen (greater than ninety-six percent).
Ability to Withstand the Fuel Tank Operating Environment	N/A
Maintenance Impact	N/A
Logistics Concerns	N/A
Technological Challenges (Why Development Not Completed, Loss of Funding)	Science and technology challenges for TALON include the following: • Development of lightweight, high-speed turbo-machines (turbo-compressor and turbo-expander) for the cryocooler. • Development of lightweight, cryogenic heat exchangers. • Minimize system weight and size. • Minimize distillation column height. • Correct for column tilt effects. • Provide bleed air pretreatment.
Status of Development (Initial, Validation, Fielded)	Initial
System Initial and Support Costs	N/A
Retrofit Impact (Costs, Integration Difficulties)	N/A
Requirements Impact (Weight, Volume, Power, Fuel Quantity Reduction…)	N/A – The technology is currently being developed.
Suppressant/Technology Utilized (Halon-Type, Water, Liquid, Gas…)	nitrogen
Expulsion Method (Utilization of Nitrogen, Nozzles…)	Utilization of Nitrogen
Effectiveness (Vs. Threat, Environment…) – list the threats tested	N/A – The technology is currently being developed.
Restart Funding Required (Cost to Reevaluate the "Moth-balled" Technology)	N/A – The technology is currently being developed.
Testing Performed (Small- Medium- Large-Scale)	N/A – The technology is currently being developed.
More advanced versions/technologies which now make it feasible (technological breakthrough)	N/A – The technology is currently being developed.
Recommended for specific type of aircraft (fighter/attack, bomber, cargo/transport)	N/A

Point of Contact	N/A
Military Service (U.S. Air Force, U.S. Navy, U.S. Army)	U.S. Air Force
Date of Development	1950s
Technology Developed	Carbon Dioxide
Mechanisms Used (How It Operates)	Inertion with carbon dioxide
Ability to Withstand the Fuel Tank Operating Environment	N/A
Maintenance Impact	The dry ice and gaseous CO_2 in bottles require servicing at the military bases. Servicing for the combustion system is dependent on whether fuel or carbon is burned. Carbon combustion would require frequent servicing. Fuel combustion would likely require only periodic maintenance for filter changes, etc.
Logistics Concerns	N/A
Technological Challenges (Why Development Not Completed, Loss of Funding)	Carbon dioxide was not pursued further because it is a greenhouse gas that adversely affects the environment. Its use might be subject to future environmental restrictions or banned completely.
Status of Development (Initial, Validation, Fielded)	N/A
System Initial and Support Costs	A cost/benefit/feasibility analysis was not performed for this report because of the lack of hardware and test data.
Retrofit Impact (Costs, Integration Difficulties)	A cost/benefit/feasibility analysis was not performed for this report because of the lack of hardware and test data.
Requirements Impact (Weight, Volume, Power, Fuel Quantity Reduction…)	A cost/benefit/feasibility analysis was not performed for this report because of the lack of hardware and test data.
Suppressant/Technology Utilized (Halon-Type, Water, Liquid, Gas…)	Carbon dioxide.
Expulsion Method (Utilization of Nitrogen, Nozzles…)	N/A
Effectiveness (Vs. Threat, Environment…) – list the threats tested	N/A
Restart Funding Required (Cost to Reevaluate the "Moth-balled" Technology)	N/A
Testing Performed (Small- Medium- Large-Scale)	N/A
More advanced versions/technologies which now make it feasible (technological breakthrough)	N/A
Recommended for specific type of aircraft (fighter/attack, bomber, cargo/transport)	N/A

Point of Contact	N/A
Military Service (U.S. Air Force, U.S. Navy, U.S. Army)	N/A
Date of Development	N/A
Technology Developed	Exhaust Gas
Mechanisms Used (How It Operates)	Inertion with exhaust gas.
Ability to Withstand the Fuel Tank Operating Environment	N/A
Maintenance Impact	N/A
Logistics Concerns	N/A
Technological Challenges (Why Development Not Completed, Loss of Funding)	• The exhaust gas must be cooled to 160 °F or less before it can be introduced into the fuel tank to protect components, fuel tank sealants, protective coatings, and fuel bladders. A large precooler would be required to reduce the gas temperature. • Modern high performance aircraft use bulk fuel in the aircraft as heat sink to dissipate the excess heat generated by the hydraulic system and frankly would be hard pressed to accept the addition of heat from exhaust gases. • A high concentration of water vapor in jet engine exhaust that would have to be removed before reaching the fuel tank. • There is also a fuel burn penalty for using exhaust or turbine gas. • There is a concern about the corrosive effects of the oxides of nitrogen and sulfur in the exhaust gases on the fuel system and tank. Filters would have to be maintained and a monitoring program would be required to avoid adverse affects to the fuel tank. • Adding to the complexity of installing an exhaust bleed-air port, engine exhaust systems will require conditioning, filtering, overheat protection and a distributing system. For estimating purposes, existing ECS systems could provide a minimum baseline for determining the size and cooling requirements of an engine exhaust system.
Status of Development (Initial, Validation, Fielded)	N/A - It is believed that this technology is not currently viable.
System Initial and Support Costs	A cost/benefit/feasibility study was not performed because of a lack of data.
Retrofit Impact (Costs, Integration Difficulties)	The collection of engine exhaust gas would require the installation of a bleed air port within the engine's turbine stage(s). Since nearly all engines use fan air to assist in cooling the engine's turbine, the location of the bleed air port would have to be properly located to avoid the fan air. Tapping into an existing engine turbine stage would require extensive and costly engine rework and recertification. There are contaminates in the exhaust gas that would have to be filtered prior to being introduced into the fuel tank. This would add to the size, cost, weight and maintenance of this method. A cost/benefit/feasibility study was not performed because of a lack of data.
Requirements Impact (Weight, Volume, Power, Fuel Quantity Reduction…)	N/A
Suppressant/Technology Utilized (Halon-Type, Water, Liquid, Gas…)	N/A
Expulsion Method (Utilization of Nitrogen, Nozzles…)	N/A
Effectiveness (Vs. Threat, Environment…) – list the threats tested	N/A
Restart Funding Required (Cost to Reevaluate the "Moth-balled" Technology)	It is believed that this technology is not currently viable. However, it may be of value to aircraft designers in the future.
Testing Performed (Small- Medium- Large-Scale)	N/A
More advanced versions/technologies which now make it feasible (technological breakthrough)	It is believed that this technology is not currently viable. However, it may be of value to aircraft designers in the future.
Recommended for specific type of aircraft (fighter/attack, bomber, cargo/transport)	N/A

Point of Contact	N/A
Military Service (U.S. Air Force, U.S. Navy, U.S. Army)	N/A
Date of Development	N/A
Technology Developed	Fuel Fogging
Mechanisms Used (How It Operates)	The system configuration consists of nozzles, filters and the necessary plumbing to flow high-pressure fuel to these nozzles. The fuel fog distribution manifold with fog nozzles must be located to produce uniform fog distribution through the fuel cells under all degrees of ullage and dynamic flight conditions.
Ability to Withstand the Fuel Tank Operating Environment	N/A
Maintenance Impact	The fuel fogging technique would increase the maintenance requirements due to the addition of pumps, filter and extra distribution lines. There is no known way to insure that the system is always operating at required performance.
Logistics Concerns	N/A
Technological Challenges (Why Development Not Completed, Loss of Funding)	N/A
Status of Development (Initial, Validation, Fielded)	N/A
System Initial and Support Costs	The fuel fogging technique would require additional plumbing consisting of nozzles, filter and lines. No specific weights or associated costs are available at this time for this technique.
Retrofit Impact (Costs, Integration Difficulties)	Same as above.
Requirements Impact (Weight, Volume, Power, Fuel Quantity Reduction…)	Same as above.
Suppressant/Technology Utilized (Halon-Type, Water, Liquid, Gas…)	N/A
Expulsion Method (Utilization of Nitrogen, Nozzles…)	N/A
Effectiveness (Vs. Threat, Environment…) – list the threats tested	• When a .30 API ignition was used, fires resulted from every impact. • Only drops below 20 micron diameter contributed to an over-rich concentration. Large drops, over 40 micron in diameter rapidly reduce the concentration of the fine mist by coalescence. • System performance is dependent on equipment capable of creating and distributing very small (5 to 50 microns) fuel particles throughout the ullage of the tank. Spraying fuel at high (500 psig) pressure through nozzles designed to produce uniform fog dispersion best does this. With the state-of-the-art equipment, system performance is limited since only partial inerting with jet fuels is possible. There is a depression in the rich flammability limit when a fuel fog is sprayed into the existing ullage of the tank. There is no known way to ensure that the system is always operating at the required performance. • With present state-of-the-art hardware, fuel tank inerting over the entire flammability range of JP-4 has not been realized. The system usage is thus limited to applications where the fuel temperature never gets more than 35°F below its rich limit. Because of this, development effort on this technology has been discontinued.
Restart Funding Required (Cost to Reevaluate the "Moth-balled" Technology)	N/A
Testing Performed (Small- Medium- Large-Scale)	N/A
More advanced versions/technologies which now make it feasible (technological breakthrough)	N/A
Recommended for specific type of aircraft (fighter/attack, bomber, cargo/transport)	N/A

Point of Contact	N/A
Military Service (U.S. Air Force, U.S. Navy, U.S. Army)	(U.S. Air Force
Date of Development	1960s
Technology Developed	Anti-Misting Fuel
Mechanisms Used (How It Operates)	The concept of anti-misting kerosene (AMK) was raised in an effort to reduce the hazard to personnel during post-crash fires. Early AMK efforts involved a soap-type chemical additive to the fuel which changed it from a liquid to a semi-solid gel. When subjected to pumping forces, the fuel behaves as a semi-liquid and can be pumped through pressurized lines. Further testing of anti-misting fuels from the mid to late 1970s examined these additives and their ability to alter the fuel mist or spray during a crash situation by creating large droplets in lieu of the fine mist. Under conditions encountered when a fuel tank ruptures on impact, the fuel exits as droplets instead of a fine mist or spray. A more recent approach used other additives to increase the shear force necessary to disperse the fuel into the fine mist that creates the major fire hazard.
Ability to Withstand the Fuel Tank Operating Environment	N/A
Maintenance Impact	N/A
Logistics Concerns	N/A
Technological Challenges (Why Development Not Completed, Loss of Funding)	The concept was dropped because of major technical problems associated with filtering out impurities and starting engines.
Status of Development (Initial, Validation, Fielded)	N/A
System Initial and Support Costs	N/A
Retrofit Impact (Costs, Integration Difficulties)	N/A
Requirements Impact (Weight, Volume, Power, Fuel Quantity Reduction…)	N/A
Suppressant/Technology Utilized (Halon-Type, Water, Liquid, Gas…)	Anti-misting fuel.
Expulsion Method (Utilization of Nitrogen, Nozzles…)	N/A
Effectiveness (Vs. Threat, Environment…) – list the threats tested	Anti-mist additives do not appreciably alter the fuel properties. In 1973, the Air Force tested AMK to determine if it produced any reduction in the ballistically-induced ullage explosion and found it ineffective in reducing the overpressures with JP-4 fuel, but effective in reducing overpressures in JP-8.
Restart Funding Required (Cost to Reevaluate the "Moth-balled" Technology)	N/A
Testing Performed (Small- Medium- Large-Scale)	N/A
More advanced versions/technologies which now make it feasible (technological breakthrough)	This idea has apparently not been pursued further.
Recommended for specific type of aircraft (fighter/attack, bomber, cargo/transport)	N/A

Point of Contact	N/A
Military Service (U.S. Air Force, U.S. Navy, U.S. Army)	N/A
Date of Development	N/A
Technology Developed	BlazeTech Inc.
Mechanisms Used (How It Operates)	Produces small gas bubbles (typically nitrogen with a diameter approximately one to three mm and a gas volume fraction of one percent) to attenuate ram pressures. These bubbles drastically alter the wave propagation properties of the liquid fuel which lower the strength of ram pressure pulses. The nitrogen also inerts the ullage space in the tank and eliminates the explosion hazard in the fuel tank. Successful development and implementation of BlazeTech's technology will result in a breakthrough in fuel tank protection that can drastically reduce the overall vulnerability of aircraft in combat and crash situations. Bubbles can be produced in a number of ways, each of which has its own advantages and disadvantages. For validation and testing purposes, the method used was the easiest conceptually to implement and the results were easiest to interpret. The system consists of a series of tubes or plates with small orifices used to distribute nitrogen bubbles throughout the fuel tank. Drawing it from the fuel tank ullage recycles the bubble gas. Some nitrogen is also added to the cycle to account for losses through the tank ventilation system. A gas-fuel separator is included in the fuel line to protect the remaining equipment in the fuel system.
Ability to Withstand the Fuel Tank Operating Environment	N/A
Maintenance Impact	N/A
Logistics Concerns	N/A
Technological Challenges (Why Development Not Completed, Loss of Funding)	Current development of the technology for a fighter aircraft application is being supported by the Air Force through a Phase II SBIR project.
Status of Development (Initial, Validation, Fielded)	initial
System Initial and Support Costs	N/A
Retrofit Impact (Costs, Integration Difficulties)	N/A
Requirements Impact (Weight, Volume, Power, Fuel Quantity Reduction…)	N/A
Suppressant/Technology Utilized (Halon-Type, Water, Liquid, Gas…)	nitrogen
Expulsion Method (Utilization of Nitrogen, Nozzles…)	Bubbles can be produced in a number of ways, each of which has its own advantages and disadvantages.
Effectiveness (Vs. Threat, Environment…) – list the threats tested	Lab scale testing has produced encouraging results. Using a hammer impact on a piston supporting a column of water, BlazeTech has achieved attenuations of more than 90 percent with void fractions (gas volume fractions) as little as one percent using nitrogen bubbles in water. A similar impact with a small fraction of gas bubbles in the water produced pressures below 100 psig.
Restart Funding Required (Cost to Reevaluate the "Moth-balled" Technology)	Current development of the technology for a fighter aircraft application is being supported by the Air Force through a Phase II SBIR project.
Testing Performed (Small- Medium- Large-Scale)	small
More advanced versions/technologies which now make it feasible (technological breakthrough)	N/A
Recommended for specific type of aircraft (fighter/attack, bomber, cargo/transport)	N/A

Point of Contact	N/A
Military Service (U.S. Air Force, U.S. Navy, U.S. Army)	N/A
Date of Development	N/A
Technology Developed	Air Purging
Mechanisms Used (How It Operates)	In a fuel system incorporating fuel management, certain tanks will empty ahead of others. If those tanks, which empty prior to entering combat, are thoroughly purged of fuel vapors, they will no longer represent an explosive hazard. Air is the preferred purging medium because it does not have to be carried in a storage container aboard the aircraft. Ram pressure, due to forward flight, can provide the motive power. Alternately, engine bleed air can be utilized. In either case, a pair of valves at the opposite extremities of the tank, are opened to provide an air purging inlet and overboard exhaust.
Ability to Withstand the Fuel Tank Operating Environment	If engine bleed air is used, care must be taken to keep the temperatures of the purging gas below the thermal limit of the fuel tank and components.
Maintenance Impact	The valve on the supply side will incur a negligible weight penalty, but should incorporate a timer to limit the fuel penalty due to bleed air extraction, which could make the use of bleed air unattractive. Ram air, on the other hand, would require a larger and heavier valve, but can be left open for the remainder of the flight.
Logistics Concerns	N/A
Technological Challenges (Why Development Not Completed, Loss of Funding)	The principal problem with purging is that a portion of the liquid cannot be transferred out of the tank, i.e., part of the unavailable fuel. If the quantity of fuel or the area over which it is spread is small, the ability of the fuel to cause damage, if hit, is small, and purging may be a good way to inert the majority of the tank. On the other hand, the use of air as the purge gas, while economical, is all that is necessary to continue a fire, once started.
Status of Development (Initial, Validation, Fielded)	N/A
System Initial and Support Costs	N/A
Retrofit Impact (Costs, Integration Difficulties)	N/A
Requirements Impact (Weight, Volume, Power, Fuel Quantity Reduction…)	N/A
Suppressant/Technology Utilized (Halon-Type, Water, Liquid, Gas…)	air
Expulsion Method (Utilization of Nitrogen, Nozzles…)	N/A
Effectiveness (Vs. Threat, Environment…) – list the threats tested	N/A
Restart Funding Required (Cost to Reevaluate the "Moth-balled" Technology)	N/A
Testing Performed (Small- Medium- Large-Scale)	N/A
More advanced versions/technologies which now make it feasible (technological breakthrough)	N/A
Recommended for specific type of aircraft (fighter/attack, bomber, cargo/transport)	N/A

Point of Contact	N/A
Military Service (U.S. Air Force, U.S. Navy, U.S. Army)	N/A
Date of Development	N/A
Technology Developed	Fuel Scrubbing
Mechanisms Used (How It Operates)	Fuel scrubbing uses inert gas to dilute the dissolved air in the fuel. This could be accomplished in the aircraft during refueling, or at the air base storage tanks. The scrubbers would be built in to the refueling system (or put inline between the truck and the aircraft) and mix the inerting gas with the fuel as the tank is filled.
Ability to Withstand the Fuel Tank Operating Environment	N/A
Maintenance Impact	N/A
Logistics Concerns	N/A
Technological Challenges (Why Development Not Completed, Loss of Funding)	N/A
Status of Development (Initial, Validation, Fielded)	N/A
System Initial and Support Costs	N/A
Retrofit Impact (Costs, Integration Difficulties)	N/A
Requirements Impact (Weight, Volume, Power, Fuel Quantity Reduction…)	N/A
Suppressant/Technology Utilized (Halon-Type, Water, Liquid, Gas…)	Nitrogen
Expulsion Method (Utilization of Nitrogen, Nozzles…)	N/A
Effectiveness (Vs. Threat, Environment…) – list the threats tested	During climb, the air in the fuel, which is mostly nitrogen due to the scrubbing, will evolve out of the fuel to the ullage. This inerts the ullage during climb and for the early portion of the cruise flight phase. However, the ullage is not inert during refueling, taxi and takeoff. Scrubbers require a minimum flow in order to work properly. If the flow from the truck or refinery is too slow, then the inert gas will not be mixed into the fuel, and it will not be inerted. The scrubber also adds some pressure drop to the system so more time would be required to fill the fuel tank(s). The primary disadvantage to fuel scrubbing is that it only works if a fuel tank receives fuel. Fuel scrubbing only gets rid of the dissolved oxygen in the fuel. Therefore, it must be used in conjunction with an ullage protection system.
Restart Funding Required (Cost to Reevaluate the "Moth-balled" Technology)	N/A
Testing Performed (Small- Medium- Large-Scale)	N/A
More advanced versions/technologies which now make it feasible (technological breakthrough)	N/A
Recommended for specific type of aircraft (fighter/attack, bomber, cargo/transport)	N/A

Point of Contact	N/A
Military Service (U.S. Air Force, U.S. Navy, U.S. Army)	N/A
Date of Development	N/A
Technology Developed	Ullage Washing
Mechanisms Used (How It Operates)	Ullage washing uses inert gas to dilute the air above the fuel. To be effective, this can only be accomplished on the aircraft. A truck or cart with inerting gas would be connected to a distribution system in the aircraft to deliver the inerting gas to the fuel tanks. Alternatively, an onboard system could provide the inerting gas to the distribution system.
Ability to Withstand the Fuel Tank Operating Environment	N/A
Maintenance Impact	N/A
Logistics Concerns	N/A
Technological Challenges (Why Development Not Completed, Loss of Funding)	• Ullage washing requires more nitrogen to inert the fuel tank than fuel scrubbing requires. • An empty tank will stay inerted until descent when the pressure change causes ambient air to enter the fuel tank. Ullage washing of a tank with a fuel quantity of 25 percent or less using NEA that contains 5 percent oxygen or less will remain inert until descent, provided there is no ventilation of the tank during operation. The combination of ullage washing and the normal drop in fuel temperature during a flight can help to limit a fuel tank's exposure to a flammable, non-inert ullage. • A combination of fuel scrubbing and ullage washing avoids the problem of evolving oxygen for nearly full tanks. The ullage oxygen concentration decreases during climb. However, as the fuel is depleted from the tanks, the oxygen concentration eventually exceeds nine percent because ambient air replaces the depleted fuel.
Status of Development (Initial, Validation, Fielded)	N/A
System Initial and Support Costs	N/A
Retrofit Impact (Costs, Integration Difficulties)	N/A
Requirements Impact (Weight, Volume, Power, Fuel Quantity Reduction…)	N/A
Suppressant/Technology Utilized (Halon-Type, Water, Liquid, Gas…)	nitrogen
Expulsion Method (Utilization of Nitrogen, Nozzles…)	N/A
Effectiveness (Vs. Threat, Environment…) – list the threats tested	There is also a potential for fuel tank structural damage if the source of inerting gas is not regulated properly. Ullage washing works well in tanks with little fuel but is ineffective in tanks that are full of fuel. Ullage washing combined with normal fuel temperature changes did prove effective.
Restart Funding Required (Cost to Reevaluate the "Moth-balled" Technology)	N/A
Testing Performed (Small- Medium- Large-Scale)	N/A
More advanced versions/technologies which now make it feasible (technological breakthrough)	N/A
Recommended for specific type of aircraft (fighter/attack, bomber, cargo/transport)	N/A

Point of Contact	N/A
Military Service (U.S. Air Force, U.S. Navy, U.S. Army)	N/A
Date of Development	N/A
Technology Developed	Fuel Tank Ullage Sweeping
Mechanisms Used (How It Operates)	A positive ventilation system may be used to "sweep" the ullage of flammable fuel vapor/air mixtures at a rate that keeps the ullage lean in spite of a higher than desirable fuel temperature. This technique essentially keeps the ullage below the lean explosive limit.
Ability to Withstand the Fuel Tank Operating Environment	N/A
Maintenance Impact	N/A
Logistics Concerns	N/A
Technological Challenges (Why Development Not Completed, Loss of Funding)	This ventilation system may be used as needed to satisfy the requirement of the regulation, but should address any negative effects such as sweeping unburned hydrocarbons into the atmosphere. Evidence that the ullage sweeping system does not leave pockets of flammable fuel vapor/air mixtures within the tank should be provided.
Status of Development (Initial, Validation, Fielded)	N/A
System Initial and Support Costs	N/A
Retrofit Impact (Costs, Integration Difficulties)	N/A
Requirements Impact (Weight, Volume, Power, Fuel Quantity Reduction…)	N/A
Suppressant/Technology Utilized (Halon-Type, Water, Liquid, Gas…)	Air, ventilation system
Expulsion Method (Utilization of Nitrogen, Nozzles…)	N/A
Effectiveness (Vs. Threat, Environment…) – list the threats tested	N/A
Restart Funding Required (Cost to Reevaluate the "Moth-balled" Technology)	N/A
Testing Performed (Small- Medium- Large-Scale)	N/A
More advanced versions/technologies which now make it feasible (technological breakthrough)	N/A
Recommended for specific type of aircraft (fighter/attack, bomber, cargo/transport)	N/A

Point of Contact	N/A
Military Service (U.S. Air Force, U.S. Navy, U.S. Army)	N/A
Date of Development	late 1960s to the mid-1970s
Technology Developed	Catalytic Combustor
Mechanisms Used (How It Operates)	The catalytic combustor utilized lower operating temperatures and produced no combustion flame. This technique utilizes nitrogen from the surrounding atmosphere as the principal component of the ballast gas admitted to the tanks. Free oxygen is reduced to safe levels by means of catalyzed reaction with a small fraction of the aircraft fuel. Before the combustion gases are admitted to the fuel tanks, the water content is reduced by condensation and by contact with a desiccant.
Ability to Withstand the Fuel Tank Operating Environment	Successful operation of a flight-configured unit achieved a very high effectiveness over a wide range of operating conditions.
Maintenance Impact	N/A
Logistics Concerns	N/A
Technological Challenges (Why Development Not Completed, Loss of Funding)	N/A
Status of Development (Initial, Validation, Fielded)	N/A
System Initial and Support Costs	N/A
Retrofit Impact (Costs, Integration Difficulties)	N/A
Requirements Impact (Weight, Volume, Power, Fuel Quantity Reduction…)	N/A
Suppressant/Technology Utilized (Halon-Type, Water, Liquid, Gas…)	Combustion gases
Expulsion Method (Utilization of Nitrogen, Nozzles…)	N/A
Effectiveness (Vs. Threat, Environment…) – list the threats tested	Inert oxygen gas concentrations below one percent were repeatedly achieved, with the generation of only a small amount of corrosive reaction products.
Restart Funding Required (Cost to Reevaluate the "Moth-balled" Technology)	N/A
Testing Performed (Small- Medium- Large-Scale)	N/A
More advanced versions/technologies which now make it feasible (technological breakthrough)	N/A
Recommended for specific type of aircraft (fighter/attack, bomber, cargo/transport)	N/A

Point of Contact	Mr. Dan Moore – DuPont
Military Service (U.S. Air Force, U.S. Navy, U.S. Army)	U.S. Air Force
Date of Development	N/A
Technology Developed	HFC-125
Mechanisms Used (How It Operates)	A tri-service representative group chose HFC-125 (a halon alternative) as the best extinguishant for subsequent development of design criteria.
Ability to Withstand the Fuel Tank Operating Environment	N/A
Maintenance Impact	N/A
Logistics Concerns	HFC-125 is easy to clean up. It leaves no residue in the event of accidental discharge. The pyrolysis products include HF and HCl. Some postfire clean up would be required. It is nonreactive with steel, aluminum, or brass. Minor swelling was evidenced in its contact with elastomers, such as Buna S, butyl rubber, and neoprene. No adverse effects are expected on plastics. Its atmospheric lifetime is 26.4 years.
Technological Challenges (Why Development Not Completed, Loss of Funding)	N/A
Status of Development (Initial, Validation, Fielded)	N/A
System Initial and Support Costs	N/A
Retrofit Impact (Costs, Integration Difficulties)	N/A
Requirements Impact (Weight, Volume, Power, Fuel Quantity Reduction…)	HFC-125 will require more agent than Halon 1301.
Suppressant/Technology Utilized (Halon-Type, Water, Liquid, Gas…)	N/A
Expulsion Method (Utilization of Nitrogen, Nozzles…)	N/A
Effectiveness (Vs. Threat, Environment…) – list the threats tested	• The following results are from the F-16 fuel tank explosion suppression replacement and baseline characterization tests. These tests were conducted to allow development of alternative approaches to the current F-16 Halon 1301 fuel tank inerting system. • Five of the 12 shots using HFC-125 against the 110-grain fragment threat resulted in an explosion. HFC-125 provided ullage protection with greater than seven percent nominal concentration. However, the actual agent volume percent used was greater than ten percent. • Kidde Technologies sells HFC-125 systems for explosion suppression in grain elevators.
Restart Funding Required (Cost to Reevaluate the "Moth-balled" Technology)	N/A
Testing Performed (Small- Medium- Large-Scale)	Tests were conducted to allow development of alternative approaches to the current F-16 Halon 1301 fuel tank inerting system.
More advanced versions/technologies which now make it feasible (technological breakthrough)	N/A
Recommended for specific type of aircraft (fighter/attack, bomber, cargo/transport)	N/A

Point of Contact	Mr. Paul Rivers – 3M Specialty Materials
Military Service (U.S. Air Force, U.S. Navy, U.S. Army)	U.S. Air Force
Date of Development	1980s
Technology Developed	FC-218
Mechanisms Used (How It Operates)	Halon alternative
Ability to Withstand the Fuel Tank Operating Environment	N/A
Maintenance Impact	N/A
Logistics Concerns	N/A
Technological Challenges (Why Development Not Completed, Loss of Funding)	N/A
Status of Development (Initial, Validation, Fielded)	N/A
System Initial and Support Costs	N/A
Retrofit Impact (Costs, Integration Difficulties)	N/A
Requirements Impact (Weight, Volume, Power, Fuel Quantity Reduction…)	FC-218 will require more agent than Halon 1301.
Suppressant/Technology Utilized (Halon-Type, Water, Liquid, Gas…)	N/A
Expulsion Method (Utilization of Nitrogen, Nozzles…)	N/A
Effectiveness (Vs. Threat, Environment…) – list the threats tested	• The following results are from the F-16 fuel tank explosion suppression replacement and baseline characterization tests. These tests were conducted to allow development of alternative approaches to the current F-16 Halon 1301 fuel tank inerting system. • Eleven of the 28 shots using FC-218 against the 110-grain fragment threat resulted in an explosion. FC-218 provided ullage protection with greater than four percent nominal concentration.
Restart Funding Required (Cost to Reevaluate the "Moth-balled" Technology)	N/A
Testing Performed (Small- Medium- Large-Scale)	These tests were conducted to allow development of alternative approaches to the current F-16 Halon 1301 fuel tank inerting system.
More advanced versions/technologies which now make it feasible (technological breakthrough)	N/A
Recommended for specific type of aircraft (fighter/attack, bomber, cargo/transport)	N/A

Point of Contact	Mr. Steve Newhouse – Newhouse International
Military Service (U.S. Air Force, U.S. Navy, U.S. Army)	N/A
Date of Development	N/A
Technology Developed	Triodide (CF_3I)
Mechanisms Used (How It Operates)	The alternative agent that is the most similar to Halon 1301 (CF_3Br) is triodide (CF_3I). CF_3I has been recognized as an effective fire extinguishing agent and a potential "drop-in" replacement for Halon 1301 in some of the non-occupied applications.
Ability to Withstand the Fuel Tank Operating Environment	N/A
Maintenance Impact	• Two characteristics have limited the acceptance of CF_3I: ◦ A relatively high boiling point (≈ -9°F for CF_3I vs. ≈ -72°F for Halon 1301) and, ◦ The perceived health hazard associated with its relatively low toxicity/cardiac sensitization level (LOAEL ≈ 0.4 percent for CF_3I vs. ≈ 7.5 percent for Halon 1301.) • Although CF_3I is as effective as Halon 1301 at suppressing fires, has almost zero ozone depleting potential (ODP) and is environmentally benign, it is a cardiac sensitizer. Therefore, the EPA has chosen to list CF_3I as a SNAP approved substitute in normally unoccupied areas. Aircraft engine nacelle fire suppression systems fall into this category. AF policy does not recommend the use of CF_3I in new systems.
Logistics Concerns	N/A
Technological Challenges (Why Development Not Completed, Loss of Funding)	The AF has opted to continue research on CF_3I as a retrofit alternative for existing systems. Preliminary analysis indicates CF_3I will be able to replace Halon 1301 with minor airframe system modifications. The F-16 airframe contractor is continuing to refine this analysis to an engineering manufacturing development status.
Status of Development (Initial, Validation, Fielded)	N/A
System Initial and Support Costs	N/A
Retrofit Impact (Costs, Integration Difficulties)	N/A
Requirements Impact (Weight, Volume, Power, Fuel Quantity Reduction…)	CF_3I provided ullage protection with greater than six percent nominal concentration.
Suppressant/Technology Utilized (Halon-Type, Water, Liquid, Gas…)	CF_3I
Expulsion Method (Utilization of Nitrogen, Nozzles…)	N/A
Effectiveness (Vs. Threat, Environment…) – list the threats tested	The following results are from the F-16 fuel tank explosion suppression replacement and baseline characterization tests. These tests were conducted to allow development of alternative approaches to the current F-16 Halon 1301 fuel tank inerting system. CF_3I was one of the candidate agents evaluated.
Restart Funding Required (Cost to Reevaluate the "Moth-balled" Technology)	N/A
Testing Performed (Small- Medium- Large-Scale)	N/A
More advanced versions/technologies which now make it feasible (technological breakthrough)	N/A
Recommended for specific type of aircraft (fighter/attack, bomber, cargo/transport)	N/A

Point of Contact	N/A
Military Service (U.S. Air Force, U.S. Navy, U.S. Army)	U.S. Air Force
Date of Development	N/A
Technology Developed	Dry Powders
Mechanisms Used (How It Operates)	Dry chemicals are very effective in extinguishing Class A, B, and C fires, depending on the agent.
Ability to Withstand the Fuel Tank Operating Environment	N/A
Maintenance Impact	• Dry powders can cause severe secondary damage to electronic and mechanical equipment and usually require major cleanup. • Another drawback is engine and fuel system component damage, including corrosion and clogging of fuel system components as well as deposition and hot-metal corrosion in the hot section of the engine. These could occur if, after explosion-triggered or accidental discharge, particulate contaminated fuel from the tank is transferred through the fuel system and eventually to the engine. Because the ability of powders to suppress explosions is related to total surface area per unit weight, powders have been most effective at seven to ten micron particle sizes. This would pass through any filters currently used in aircraft fuel systems. Research indicates, however, that the powder would agglomerate, forming a sludge in the bottom of the fuel tank. It is probable that the agglomerated clumps of powder would be trapped in the fuel system filters. If the filters are plugged by the clumps, and the system reverts to bypassing the fuel around the filter, there is a possibility of clogging the engine fuel controls and combustor nozzles. • In high performance aircraft, fuel is constantly being moved around as a part of the thermal management system. It is conceivable that some contaminated fuel could pass through pumps and valves, etc. more than one time with today's recirculation systems.
Logistics Concerns	N/A
Technological Challenges (Why Development Not Completed, Loss of Funding)	N/A
Status of Development (Initial, Validation, Fielded)	N/A
System Initial and Support Costs	N/A
Retrofit Impact (Costs, Integration Difficulties)	N/A
Requirements Impact (Weight, Volume, Power, Fuel Quantity Reduction…)	N/A
Suppressant/Technology Utilized (Halon-Type, Water, Liquid, Gas…)	N/A
Expulsion Method (Utilization of Nitrogen, Nozzles…)	N/A
Effectiveness (Vs. Threat, Environment…) – list the threats tested	The limiting factor with powders is speed of delivery. Finer powders equate to increased effectiveness. In fuel tanks, the powder may have to travel some distance to reach the explosion flame front before it propagates. Elementary ballistics show that speed of delivery decreases with decreasing powder grain size due to velocity losses. Therefore, larger powder grains would be required to extinguish the ullage explosion before lethal overpressures are reached. These larger powder grain sizes would decrease the effectiveness of the powder in extinguishing the combustion once it got there. Dry powders only work if they are dry. Therefore, any ullage protection system will need appropriate packaging to assure a dry condition of the powder.
Restart Funding Required (Cost to Reevaluate the "Moth-balled" Technology)	N/A
Testing Performed (Small- Medium- Large-Scale)	N/A
More advanced versions/technologies which now make it feasible (technological breakthrough)	N/A
Recommended for specific type of aircraft (fighter/attack, bomber, cargo/transport)	N/A

APPENDIX D

NOZZLE MANUFACTURERS

NOZZLE MANUFACTURERS

Spraying Systems Co. P.O. Box 7900 Wheaton, IL 60189-7900 V: 630-665-5000 F: 630-260-0842 Info@spray.com http://www.spray.com	BETE Fog Nozzle, Inc. 50 Greenfield Street Greenfield, MA 01301 V: 413-772-0846 F: 413-772-6729 http://www.bete.com